DESIGN OF A NUCLEAR POWERED, DEEP WATER, SHIP-SERVICED NAVIGATIONAL BUOY

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ABSTRACT

The advent of useful isotopic power generation and requirement for higher powered, extended service deep water navigational buoys has inspired the blending of these into a functional design. Realizing existing buoy tender limitations, a design was undertaken to utilize the largest buoy, the 8x26, and alter it to incorporate the maximum in deep water navigational aids powered by a thermoelectric isotope generator. With a five year on-station lifetime goal, each buoy subsystem was thoroughly evolved and designed, and combined to form a total system with favorable economical, safety, maintenance, and practical aspects. This theoretical derivation and integration with practical application is the object of this thesis.

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INTRODUCTION

With the constant periodic overhaul and maintenance of navigational buoys being a great consumer of both fiscal and manpower reserves of the Coast Guard, there is a pressing demand for an economical, efficient new series of outer harbor, deep water navigational buoys. Realizing existing buoytending limitations, I propose to design an efficient nuclear powered, deep water buoy which will meet current safety, fiscal, ship-established and maintained, and operational criteria.

As a practical starting point, I thoroughly reviewed the two largest existing Coast Guard navigational buoys, the 9x38 and 8x26. Here the numbers are defined as follows: the first represents the maximum diameter (in larger buoys this is the diameter of the buoy body), and the second or final number is the overall maximum vertical height. This coding system greatly facilitates discussion of all buoy types. Likewise the SNAP-7D isotope powered buoy program of 1964 was thoroughly studied to eliminate earlier errors committed. Of the 24,000 buoys the Coast Guard maintains, some 4,000 are lighted buoys, of which, two-thirds are the 9x38 and 8x26 class deep water buoy. After an optimization study of buoy functions and thorough selection of an isotope and compatible thermoelectric generator pairing, a stable buoy was designed to accommodate the dual isotope power and functional aid purposes.

Chronologically the design evolved as follows. First, the optimum in buoy functions was established by inclusion of

the most desirous navigational aids. Once the power level needed for operation was established, the type and amount of isotope power was derived as was the accompanying form of power conversion. The attached computer program was then devised to calculate an acceptable lead shield to meet current Atomic Energy Commission and National Bureau of Standards radiation safety criteria. As designed, this buoy can only be utilized inside the twelve mile limit due to inherent Atomic Energy Commission licensing procedures and jurisdiction. A complete mathematical derivation of the buoy body and shape then ensued combining the isotope power package, buoy functions, and buoy shape into a seaworthy, stable aids to navigation platform which could be serviced and maintained by the standard 180 foot class Coast Guard buoy tender. It was then necessary not only to devise an acceptable mooring system, but to protect it from the hostile marine growth and sea water electrolysis environment. Notably both the buoy design and mooring system selection were fully augmented by attached computer work.

Once these procedures were complete, the design was essentially complete as there are neither funds nor materials for proper model testing and evaluation. I did, however, attempt in the conclusions and recommendations sections to tie this theoretical thesis into the practical reality of current policies of design, development, and production--this I believe to be a key aspect of the true intention of this thesis.

BUOY FUNCTIONS

The function of a deep water outer harbor buoy is to provide an efficient reliable marker for entry into the vast network of coastal buoyage systems while minimizing the inherant hazards of shallow water navigation. With such an important role, the outer harbor buoy should incorporate the optimum in navigational locating devices to assure maximum effectiveness. Unfortunately, existing battery or acetylene powered systems have at best a two year maximum on-station time, hence large ship servicing requirements; second, the extreme hostile conditions of marine growth and salt water limit the mooring subsystem useful life to less than three years; and third, the buoy tenders capacity is limited by the working load of the boom to twenty tons. As isotopic power source provides constant reliable light weight power over long periods, the types of navigational devices on the buoy can be greatly increased.

To be functional, the buoy must be detected by any of the four established means: its outline or light; its sound producing equipment; its "being seen" radarwise; and installed radiobeacons. Under advisement of several reports (35,37,54)* into the optimum utilization of Coast Guard aids to navigation devices, I have arrived at the following as the best combination of navigational aids: electric light flasher, radiobeacon, mechanical gong, radar reflector, sonar reflector, and radar-beacon. Each of these aids is well tested and currently in

*Numbers in parenthesis refer to specific works listed in the references section.

use throughout the Coast Guard (20). Briefly each of these devices may be defined and represented as follows:

A. Mechanical Gong

Here the three standard copper-silicon clanker type gongs will be utilized to strike the copper-silicon bell located at the top of bell's own tower inside the outer tower which supports the flashing light. The gongs themselves are attached by flexible hinges to the top sides of the inner tower, and act in pendulum fashion when activated by the pitch, heave, roll, and sway of the buoy in response to wave and wind action. A separate gong tower is used to minimize vibrations to electronic equipment on the flashing light tower. Coast Guard tests (20) have established the range of the "chime" device to be 0.3 miles for normal sea conditions. No electrical powering is needed.

B. Radar Reflector

As commercial shipping and fishing vessels are the primary users of these outer buoys (35), it is imperative to establish a readily detectable buoy radarwise, as radar equipment is standard for most larger vessels. Thus our detection will be based on the standard commercial radar--the three centimeter (x-band) with a 0.5 blip-scan ratio where

$$\text{blip-scan ratio} = \frac{\text{number of times target seen}}{\text{number of times antenna turns}} \qquad [1]$$

Utilizing an existing empirical relation for buoy radar range

$$R = \sqrt{1.4\ A_R + 0.5\ A} \qquad [2]$$

where:

R = range in miles*

A_R = radar reflector area in square feet

A = remaining buoy metallic area in square feet

From experimental work utilizing the standard shape of this buoy, the range is found to be 7.5 miles (20). The reflector itself is structurally the upper middle portion of the flashing light tower, just above the gong tower. This calculation was naturally assumed for calm water conditions. No electrical power is required.

C. Sonar Reflector

As the buoy must also serve as a navigational aid to submersibles, it is advantageous to modify the counterweight portion of the buoy to provide a passive sonar reflector. For a comparative radar reflector area it is estimated that the detection range will drop to approximately two miles due to poorer underwater detection capabilities. Thus although this range is somewhat limited it does nevertheless provide yet another degree of buoy detection flexibility. Again, no power is needed.

D. Visual Detection

Obviously the buoy must also have a visual detection system for location in daylight hours by the unaided eye.

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*All references to miles denote nautical miles.

Using the following criteria; unaided eye, normal sea conditions, sea horizon background, no obstructions, and observer at sea level, an empirical formula (20) has been established to define a visual range, this being

$$R = \frac{\sqrt{A}}{6076 \tan (0°15')} \qquad [3]$$

where:

A = vertically projected area above waterline in square feet

R = range in miles

as established by the Coast Guard Field Testing and Development Unit. Thus, with this special buoy, the range is established to be some 4.4 miles; to also assist in visual detection, a simple system of buoy coloring end markings has been evolved which is consistent with the above formula. The criteria for this system's lettering is: height, fourteen inches, and width, eleven inches. The specific coloring and markings used will be as per Coast Guard buoyage system designation.

E. Radar Beacon

Perhaps one of the newest navigational devices is the radar beacon, acronym racon, which operates as follows; a standard ships x-band (three centimeter) radar signal will be received on the racon antenna and activate the racon which in return transmits a coded pulse series which is displayed directly on the ship's radar console. Recent tests have shown that the new transistorized racons can be detected from

buoys some nine miles away, and although weighing only 35 pounds and occupying a volume of about two cubic feet, it has an expected lifetime of some seven years. Based on a 12 volt, direct current system, only one watt of power is required to operate this transistor package. The racon device itself will be situated inside the buoy body for protection, while the antenna will be located directly beneath the flashing light.

F. Radio Beacon

One of the more reliable and well used offshore navigational aids is the radiobeacon. Here it is advantageous to use a Class C radiobeacon, namely the TB-107 with LSR-803A converter. This twenty mile range device requires only some twenty-five watts of electrical power, and has dimensions of 16.5 x 21.5 x 22.8 inches. The device itself is situated in the buoy body for protection, while the transmitter is located directly above the radar reflector. Operating in the 275-325KC band, the duration of pulses for the device should be limited to short periods due to power considerations; estimate transmission burst duration to 15 seconds. As would be expected, both the radarbeacon and radiobeacon are severely limited detectionwise by height above sea level, and their usefulness would rapidly decline in stormy, rough weather.

G. Electric Light Flasher

Perhaps the most important navigational aid is the electric light flasher system. Not only is night time identification abetted, but it is the primary identification

means in stormy, inclement weather. Thus this critical aid is designed to optimum effectiveness. For the twelve volt direct current system, thirty watts is needed to power this 13,000 candlepower, 360° fan beam, 3,000 amp-hour system. Specifically, the FU-840 flasher (4 second flash) and FU-1297 lamp-changer (6 bulb unit) will integrate into this system to provide a detection range of 4.6 miles for an observer at sea level when situated at a focal height of 15.9 feet. For the above parameters, the range can be found from

$$D = 1.04\sqrt{H} \qquad [4]$$

or as modified by the refraction of air and curvature of the earth

$$D = 1.15\sqrt{H} \qquad [5]$$

where:

D = range in miles

H = focal height in feet

The physical flashing code utilized will be determined by actual buoy location, but for detection purposes an occulting (light longer than dark period) is recommended, based on the following criteria

$$T = \frac{tw}{2\pi F} \qquad [6]$$

where:

T = duration of flash in seconds

t = time for one revolution

w = width of beam in centimeters

F = focal distance in centimeters

Likewise for long flashing sequences, the Blondel-Ray relation for intensity must be included, namely

$$I_{eff} = I_{init} \frac{t}{t+0.1} \qquad [6a]$$

where:

t = contact closure time in seconds

I = incandescence in candlepower

A 200 millimeter lantern will protect the clear bulb (100% transmission effectiveness) from external elements. Buoy stability is a must for this system to function effectively; the buoy is designed to ride waves solely in a vertical manner, as a dipping or swaying from the perpendicular will greatly decrease the light's effectiveness and range. The power for this as well as all other aids is provided directly from nickel-cadmium batteries installed in the buoy body. Although nickel-cadmium batteries are consistent with a five-year unattended mission, the ultimate in lampchangers, which is incorporated in this design, has a 650-day life expectancy.

All buoy functions are summarized in Tables I and II.

TABLE I

SUMMARY OF BUOY NAVIGATIONAL AIDS

Specific Aid	Power (watts)	Range (miles)	Comments
Mechanical Gong	0	0.3	Copper-silicon bell and clankers own special inner tower
Radar Reflector	0	7.5	Designed especially for 3 centimeter (x-band) radar on flashing light tower
Sonar Reflector	0	2.0	Underwater buoy and counterweight portion
Visual Detection	0	4.4	Coloring and marking systems
Radar Beacon	1.0	9.0	12 volt, D.C., Transistorized seawatch model on flashing light tower
Radio Beacon	25.0	20.0	Class C beacon, type TB-107, for 12 volt, D.C. on flashing light tower
Flashing Light	30.0	4.6	12 volt, D.C. system, 360° fan beam, 13,000 candlepower, FU-840 flasher, FU-1297 lamp-changer at top of own special tower
Total power needed	56.0		

TABLE II

NAVIGATIONAL AIDS--COSTS AND CHARACTERISTICS

Specific Aid	Mechanical Gong	Sonar Reflector	Radio Beacon	Radar Reflector	Racon	Flashing Light
Measured Phenomena	Audio System	Acoustic System	Signal Null	Radar Blip	Radar Blip	Visual System
User X Mission	Passive	Active for Homing	Passive for Homing	Passive for Homing	Active for Homing	Passive-Eye
Range Day	0.3m	2.0m	20.0m	7.5m	9.0m	4.6m
Night	0.3m	2.0m	20.0m	7.5m	9.0m	4.6m
24 hr. Availability	yes	yes	yes	yes	yes	yes
System Accuracy Upped	no	yes-bigger area	no	yes-bigger area	power up antenna up	candle-power up focal wt. up
Basic Accuracy	human ear	power up freq. down $\pm 5°$	$\pm 3°$	need 2 for fix	need 2 for fix	0.5 to 1°
Augmented Accuracy	same	water temp.	none	same	same	vary
User Cost	0	varies	>$125	radar set	radar set	0
User Size Equip.	0	varies	9"x6"x3"	12"x18"x18"	12"x18"x18"	0
Power Consumption	0	0	25 watt	0	1 watt	30 watt

TABLE II (con't)

Specific Aid	Mechanical Gong	Sonar REflector	Radio Beacon	Radar Reflector	Racon	Flashing Light
Voltage	0	0	12 volt, D.C.	0	12 volt, D.C.	12 volt, D.C.
Status of Availability	many	few	few	good	few	many
Partially Obsolete	no	no	no	no	no	no
Number of Suppliers	>10	<10	>10	>10	<5	>10
Time for Position	instant general bearing	instant bearing	3-5 min.	instant	instant	to 3 min.
Readout	none	on sonar	on RDF	on radar	on radar	direct
Auxiliary Equip. needed	none	navigational charts	navigational charts	Navig. charts	Navig. charts	Navig. charts
Using training time	none	few hrs.	few hrs.	few hrs.	few hrs.	1/2 hr.
Availability of Maintenance	good	good	good	good	good	good
Uncertainties	sound propagation in fog, wind, and sea state	blind spots, water condition, thermoclines	night effect other station overlap	positive buoy identification sea conditions	positive buoy identification sea state	positive buoy identification weather conditions

TABLE II (con't)

Specific Aid	Mechanical Gong	Sonar Reflector	Radio Beacon	Radar REflector	Racon	Flashing Light
No. people for user	1	1	1	1	1	1
Power limit	0	0	12.4 watt	0	0	~0
No. station for position	cannot get fix	1 lop 2 fix	1 lop 2 fix	1 lop 2 fix	1 lop 2 fix	1 lop 2 fix
Frequency Band	0	vary	285-325kc.	vary	vary	n.a.
Cost one station	$100	$100	$7500	$800	$300	$200
Cost maintain station	~0	~0	$500	~0	~0	~$38
Size of Equip.	5 ft^2	20 ft^2	vary	44 ft^2	20 ft^2	5 ft^2
Remarks	copper-silicon materials	outer counter-weight section	class C type	painted steel	seawatch 300	200 mm lantern

RADIOISOTOPE SELECTION

The proper selection of the powering isotope is a major consideration in a project of this type. Of the more than one thousand isotopes known to man, only 122 have potential as heat sources; quite a technological advance since the discovery of radioisotopes by mass spectrometry earlier this century by Sir J. J. Thomson. As this buoy design is an attempt to optimize this device, a thorough study of all 122 heat isotopes will be conducted with a "fatal flaw" elimination procedure to select the best isotope for this unique task.

To assure the utility of any isotope as a heat source, it must display the following characteristics:

1. A one to one hundred year half-life (some fifty isotopes).
2. A material which can exist in high concentration as a stable, inert solid at operating temperatures.
3. Must have a heat output greater than 0.1 watt/gram of pure isotope.

Likewise, the isotope must have characteristics which would assure future, economical, and practical multigram production, namely:

1. If a fission product, fission yield must be greater than 0.1%.
2. Must have sufficient information at present to define a realistic production process.
3. Isotopic separations not required for either target or product in irradiation process.

4. In irradiation, the target must not be rare, too costly, or practically unobtainable.
5. Should be not more than three steps in chemical processing and two steps of neutron irradiation in entire processing scheme.
6. For irradiation processes, thermal cross section for product should not exceed 1500 barns.
7. Similiarly the thermal neutron cross section of the target should be greater than 2 barns.
8. Cost considerations indicate an upper ceiling of \$2000/watt for the delivered isotope.

Using the above criteria, a general roster of all isotope heat sources was established as Table III. Then from this listing, three tables were constructed; Tables IV, V, and VI respectively, to delineate isotope sources because of separation processes, impractical production processes, and other rejection criteria. This reduced the number of acceptable isotopes to eight, which are listed with their respective properties in Table VII; now a final selection was made from these attractive isotopes.

Thus, additional practical selection criteria need be applied, namely:

1. Excessive gamma activity to be avoided if possible.
2. As half-life goes up, specific heat (number watts/gm) goes down.
3. As half-life goes down, power density (watts/cc) goes down.

4. Adaptability of isotope to heat conversion device.
5. Matching of isotope output to sensitive, complex electronic equipment.
6. Minimize inefficient bremsstrahlung radiation.
7. Thus an approximate ideal half-life of ten years.
8. Lessen biological hazard.
9. Minimize weight of shielding.
10. Isotope available in large quantities.
11. Isotope to have competitive costs with standard fuels (batteries and acetylene for buoys).
12. Allowable 1/2 year lag in replacement fuel cell receipt.
13. Daughter products in decay scheme should have properties no worse than original power isotope.
14. Be adaptable to marine environments.
15. Have stable compounded fuel form.

Obviously there are some conflicting requirements above, but the selection will incorporate the best combination of all factors. Utilizing these factors, the selection narrowed to two equally attractive selections, Strontium-90 and Promethium-147. Naturally each did have associated negative features: Strontium-90 had significant bremsstrahlung radiation, remarked radiation hazards, and needed heavy shielding; while Promethium-147 had an extremely short half-life, low power density, and high production costs. The problem was resolved with a telephone conversation with

Mr. W. K. Eister, Head of Isotopic Research and Development at the Atomic Energy Commission's Facility at Oak Ridge, Tennessee. Briefly, Mr. Eister reviewed the experimental results and ensuing agency policy as follows. (57)

While Promethium had proven hopeful in earlier development and testing, the prohibitive costs and short half-life--specific power combination had precluded its use in current design work. Present plans are directed towards Strontium-90 as a low power source and Plutonium-238 for higher power needs. An extremely reliable backup source for either power demand is Cobalt-60. This is the current state-of-the-art in isotopic power development, especially for static systems as called for by this unique power requirement. This selection is quite attractive in that Strontium-90 is obtained from reactor fuel wastes, an ideal reclaimation process, as these wastes would normally simply be disposed of. Further developments are in process to increase power potential using dyanmic systems, but existing policy is to promote the above mentioned fuels as it is economically desirable to increase current isotope markets as fixed costs are not obtainable. Hence the more the demand the lower the costs, thus making isotopes economically competitive with fossil fuels. In fact, studies have shown that isotope power is economically competitive with chemical and solar sources up to 500 watts. Nuclear isotopes have the major advantage against contemporary fuels in that for a given amount of fuel, they contain the largest amount of energy.

The technology of existing static systems has been thoroughly explored and Strontium-90 and Plutonium-238 have such decided advantages that numerous off-the-shelf devices are now presently available. Present Atomic Energy Commission sponsored isotope development programs are in the areas listed below:

1. Increase reliability of generators.
2. Decrease specific weight.
3. Minimize ground handling.
4. Studies of dispersion and deposition of materials.
5. Continued review of public health and safety.
6. Fission product recovery increases.
7. Actively promote isotopic usage.
8. Develop dynamic power capabilities.

Thus Strontium-90 is selected, and its unique decay scheme is presented in Figure 1. Strontium-90's short lived companion isotope, Strontium-89, an energetic beta emitter, is removed by an aging period before fuel encapsulation. Strontium-90's half-life is sufficiently long such that the drop in thermal power density over the buoy five-year cycle is relatively small and therefore neglected as related in Figures 2 and 3. In fact, the SNAP 7D program reported a less than 3% drop over a five-year test period. The daughter product Yttrium-90, does produce more energetic beta rays and a few gamma rays (0.02%), but its half-life and activity during the five year lifetime is such that its effects are quite secondary in the design. This is graphically shown in Figure 4. Fortunately the next decay step produces the stable

element, Zirconium-90, which thus eliminates the problem of shielding long-lived decay chains.

As Strontium-90 has been selected as the isotope, it is now desirous to place this in a highly effective, concentrated form, acceptable to this marine application. Commercially there are five distinct forms in which Strontium-90 can be compounded; but only Strontium Oxide, SrO, and Strontium Titanate, $SrTiO_3$, are economically feasible. Although the oxide form has very attractive qualities, especially for terrestial applications; it has a relatively high solubility in liquids, a serious safety drawback for maritime applications. The titanate form, however, has the incredible solubility of only 0.005 ppm/hour at 120°F (or some 900 years to dissolve the standard $SrTiO_3$ pellet) in either fresh or salt water, (14) a highly desirous quality, considering the possibility of a marine radiation accident. The complete physical and mechanical properties of Strontium Titanate are denoted in Table VIII. Thus, although all its properties are acceptable, the Strontium-90 compound fuel selection is based entirely on the safety criteria for a marine environment of a minimum solubility and its general chemical stability. The actual production process is denoted in Figure 5.

With the best isotope now in its most useful compound form, a computer program was established, Tables XII and XIII, to facilitate the design of an efficient, compatible power generator.

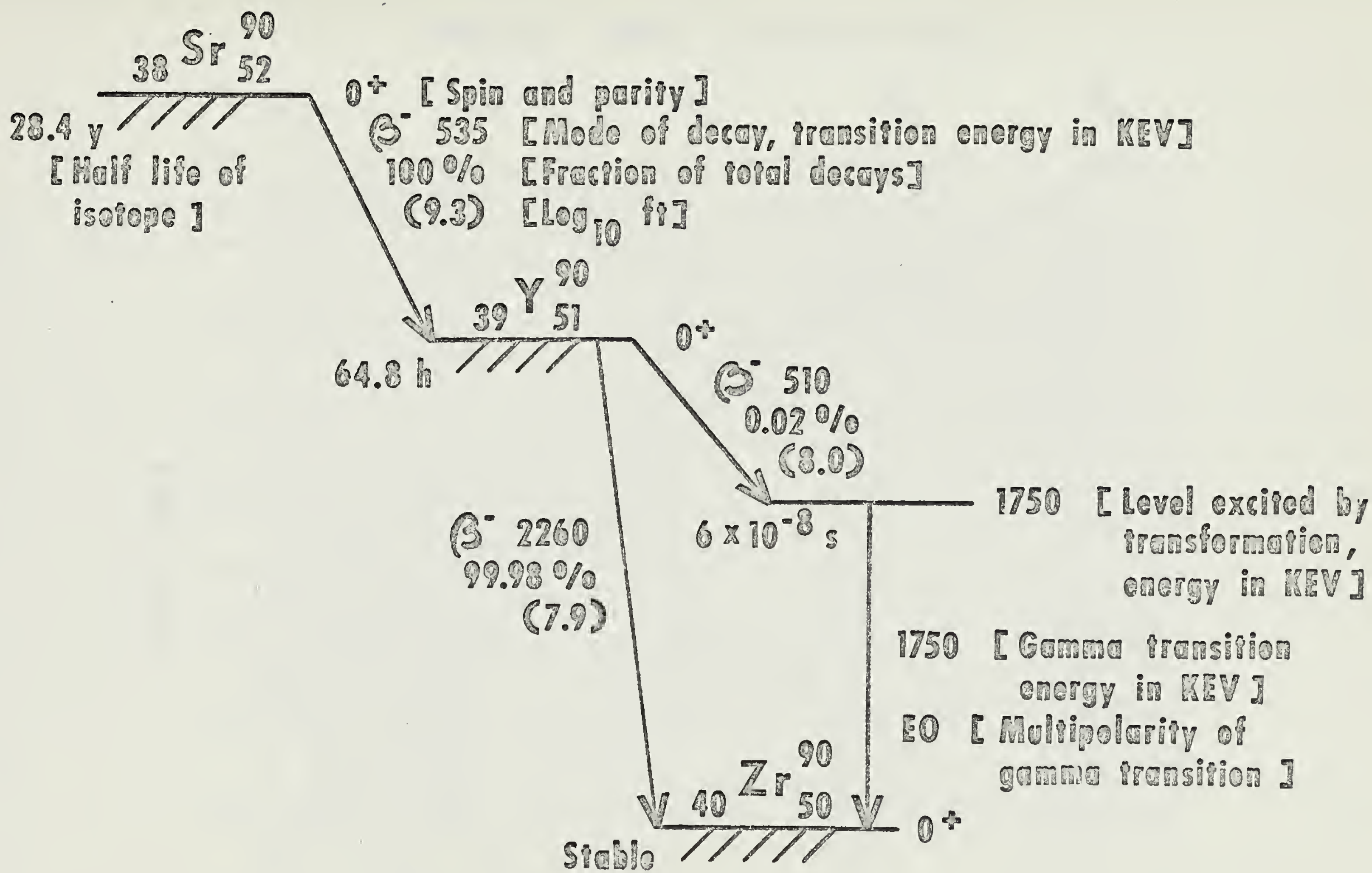

Figure 1 - Strontium-90 Decay Scheme

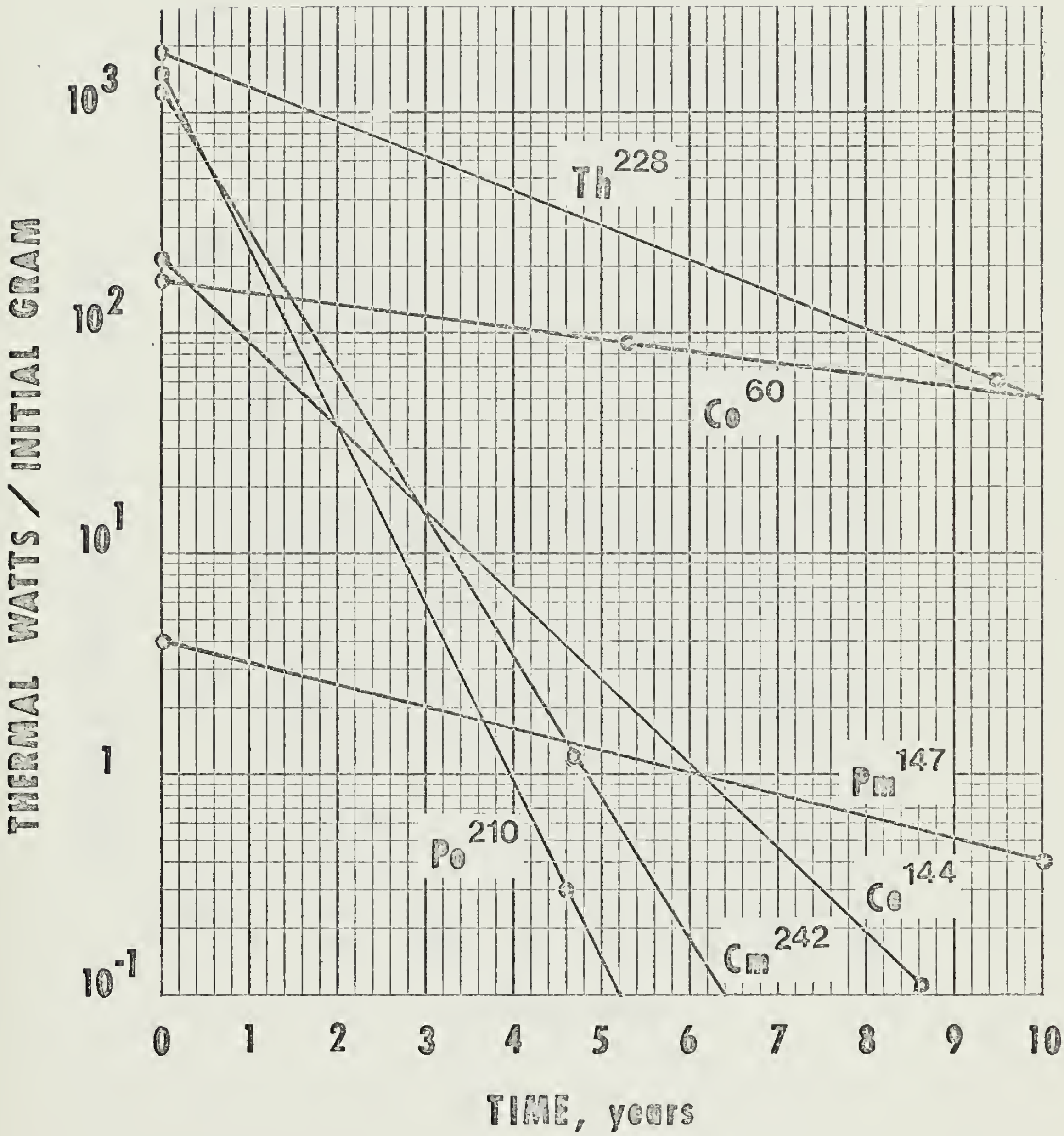

Figure 2 - Thermal Power Versus Short Lived Radioisotopes

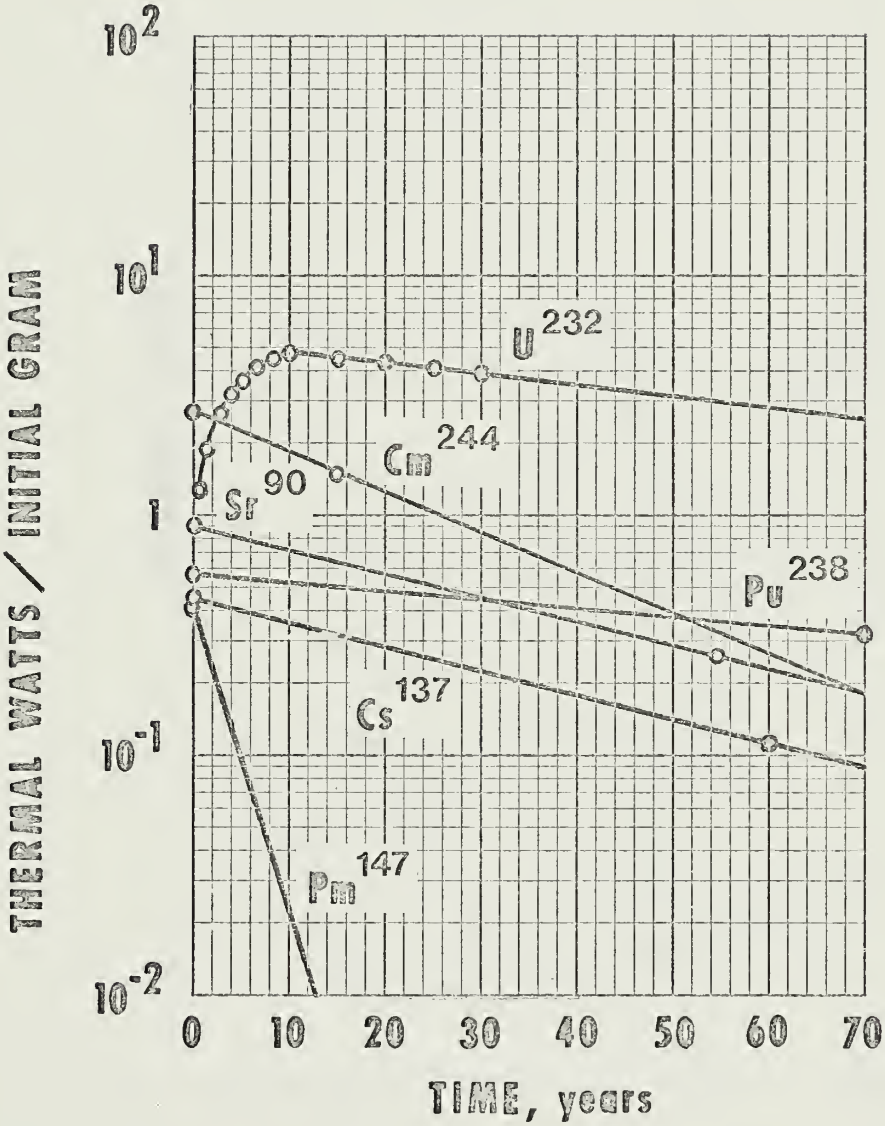

Figure 3 - Thermal Power Versus Short Lived Radioisotopes

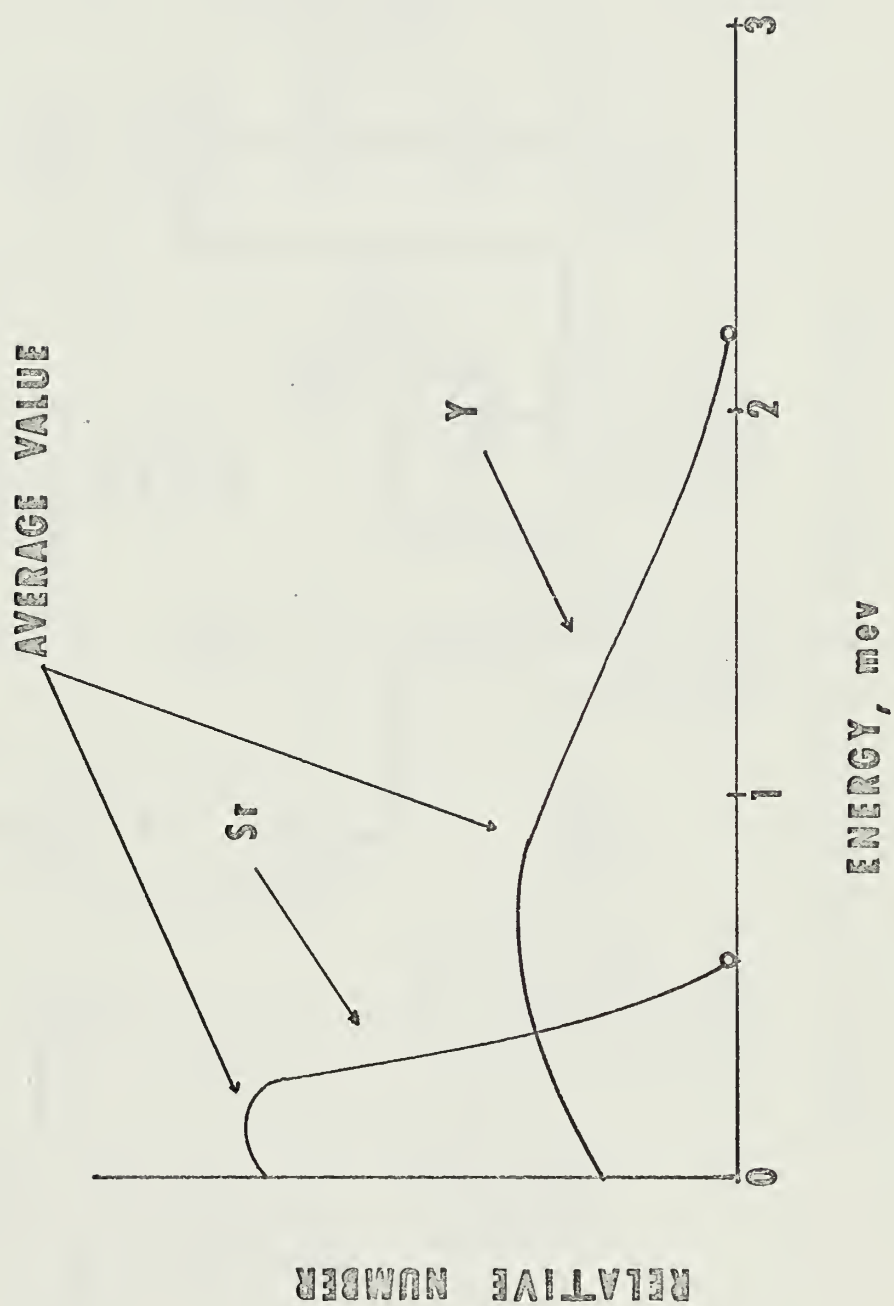

Figure 4 - Beta Energetics Diagram

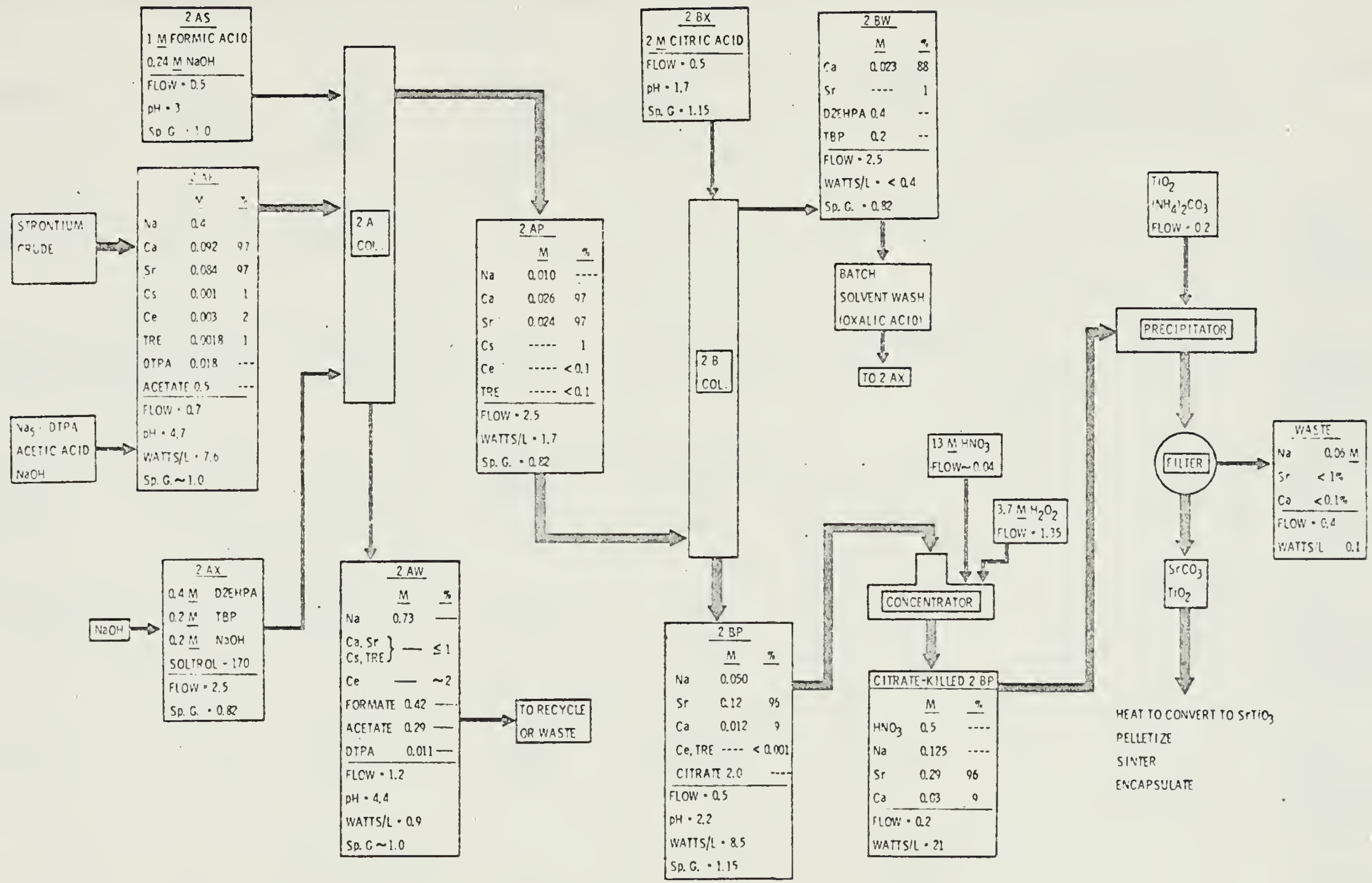

Figure 5 - Production of Strontium Titanate

TABLE III

POTENTIAL POWER RADIOISOTOPES WITH 1 TO 100 YEAR HALFLIVES

Isotope	Half-life years	Watts per gram	Isotope Separation Required		Fission Yield	Production Feasibility			Comment
			Target	Product		High	Mod	Low	
Actinium-227	21	14.3	no	no	---			x	Very rare natural isotope
Antimonium-125	2.7	2.9	yes	no	0.036			x	Too low a fission yield
Argon-42	3.5	---	no	yes	---			x	Noble gas
Barium-133	7.5	---	yes	yes	---			x	Low cross section
Bismuth-207	30	---	---	---	---			x	No feasible economic production process
Cadmium-109	1.3	---	yes	yes	---			x	Low concentrations in nature
Cadmium-113^m	14	0.35	---	yes	0.012			x	Very low fission yield

TABLE III (con't)

Isotope	Half-life years	Watts per gram	Isotope Separation Required		Fission Yield	Production Feasibility			Comment
			Target	Product		High	Mod	Low	
Californium-250	10	5.1	no	no	---			x	Multistep irradiation needed
Californium-252	2.6	4.6	no	no	---			x	Multistep irradiation needed
Cesium-134	2.1	6.8	no	yes	---			x	Cross section of product higher than that of target
Cesium-137	30	0.46	---	no	6.0	x			Well known with a simple technology
Cobalt-60	5.3	17.4	no	no	---	x			Well known with a simple technology
Curium-243	32	1.4	no	yes	---			x	Isotopic separation is detriment
Curium-244	18	2.8	no	no	---	x			Obtain from plutonium reactors

TABLE III (con't)

Isotope	Half-life years	Watts per gram	Isotope Separation Required		Fission Yield	Production Feasibility			Comment
			Target	Product		High	Mod	Low	
Einsteinium-254	1.3	---	no	no	---			x	Multistep Irradiation needed
Europium-152	13	0.79	yes	yes	---			x	Cross section too high
Europium-154	16	0.76	yes	yes	---			x	Cross section too high
Europium-155	1.7	0.91	yes	yes	0.03			x	Very low fission yield
Gadolinium-162	1	---	---	yes	---			x	Isotopic separation too complicated
Hafnium-172	5	---	---	---	---			x	No apparent production process
Hydrogen-3	12.3	0.47	yes	no	---	x			Produced on a large scale
Holmium-166	30	---	no	yes	---		x		No large scale production possibilities
Iron-55	2.7	---	yes	yes	---			x	Very low cross section

TABLE III (con't)

Isotope	Half-life years	Watts per gram	Isotope Separation Required		Fission Yield	Production Feasibility			Comment
			Target	Product		High	Mod	Low	
Krypton-85	10.4	0.71	---	yes	0.3	x			A noble gas
Lead-210	21	0.29	---	---	---			x	Very rare natural isotope
Lutetium-173	1.4	---	---	---	---			x	No feasible economic production process
Neptunium-235	1.1	---	---	---	---			x	No feasible economic production process
Niobium-93	12	---	---	---	---			x	No practical production process available
Osmium-194	2	---	yes	yes	---			x	Very rare target isotope
Plutonium-236	2.9	19.2	---	yes	---			x	Isotopic separation problems
Plutonium-238	89	0.56	no	no	---	x			Produced on large scale quantities
Plutonium-241	13	---	no	yes	---			x	Isotopic separation problems

TABLE III (Con't)

Isotope	Half-life years	Watts per gram	Isotope Separation Required		Fission Yield	Production Feasibility			Comment
			Target	Product		High	Mod	Low	
Polonium-208	2.9	17.8	---	---	---			x	No practical production process available
Promethium-144	1.1	---	---	---	---			x	No apparent production process
Promethium-145	18	---	---	---	---			x	No feasible production process
Promethium-146	2	4.6	---	---	---			x	No feasible production process
Promethium-147	2.5	0.41	---	no	2.6	x			Well known technology and availability
Radium-228	6.7	---	---	---	---			x	Very rare natural isotope
Rhodium-101	5	---	---	---	---			x	No feasible production process known
Ruthenium-106	1	31	---	yes	0.38	x			Difficult technology

TABLE III (con't)

Isotope	Half-life years	Watts per gram	Isotope Separation Required		Fission Yield	Production Feasibility			Comment
			Target	Product		High	Mod	Low	
Samarium-151	90	---	---	yes	0.45			x	Too low a heat potential
Silver-108	5	---	yes	yes	---			x	Isotopic separation problems
Sodium-22	2.6	25.4	no	no	---			x	No known practical production process
Strontium-90	28	0.95	---	no	5.9	x			Well known technology and excellent availability
Tantalum-179	1.6	---	---	---	---			x	No practical production process known
Terbium-157	30	---	---	---	---			x	No practical production process known
Thallium-204	3.9	1.2	no	yes	---			x	Difficult isotopic separation
Thorium-228	1.9	170	no	no	---	x			Well known technology and availability

TABLE III (con't)

Isotope	Half-life years	Watts per gram	Isotope Separation Required: Target	Isotope Separation Required: Product	Fission Yield	Production Feasibility: High	Production Feasibility: Mod	Production Feasibility: Low	Comment
Thulium-171	1.9	0.27	yes	no	---		x		Rare target element
Tin-121	5	---	yes	yes	---			x	Cross section too low
Uranium-232	74	4.4	no	no	---	x			Well known technology and availability

TABLE IV

ATTRACTIVE ISOTOPES REQUIRING SEPARATION PROCESSES

Isotope	Half-life years	Watts/GM	Cross Section Target	Product
Antimony-125	2.7	2.9	0.2	---
Cadmium-113^m	14.0	0.35	---	---
Cesium-134	2.1	6.8	31.0	134.0
Holmium-166	30.0	---	64.0	---
Iron-55	2.7	---	2.5	---
Silver-108	5.0	---	40.0	---
Thallium-204	3.9	1.2	11.0	---

TABLE V

ISOTOPES WITH NO PRACTICAL PRODUCTION METHODS

Isotope	Half-life years	Type of Radiation
Bismuth-207	30.0	Beta, Gamma
Hafnium-172	5.0	Beta, Gamma
Lutetium-173	1.4	Beta, Gamma
Neptunium-235	1.1	Alpha
Niobium-93	12.0	Weak Gamma, internal trans.
Polonium-208	2.9	Alpha, Gamma
Promethium-144	1.1	Gamma
Promethium-145	18.0	Beta
Promethium-146	2.0	Beta, Gamma
Rhodium-101	5.0	Weak Gamma, internal trans.
Sodium-22	2.6	Beta, Gamma
Tantalum-179	1.6	Beta, Gamma
Terbium-157	30.0	----

TABLE VI

POTENTIAL HEAT-SOURCE ISOTOPES WITH ADVERSE FACTORS

Isotope	Half-life years	Reason for Rejection
Actinium-227	21	Very rare, target isotope of radium-126 very costly
Argon-42	3.5	An inert gas. Insufficient time before of Argon-41 half-life to assure high yield.
Barium-133	7.5	Requires isotopic separation target of barium-132 extremely low (0.097%) in barium concentrations
Cadmium-109	1.3	Requires isotope separation for both target and product. Cadmium-108 concentration naturally (0.88%) too low.
Cadmium-113^{m}	14	Fission product of very low fission yield (0.012%)
Californium-250	10	Multistep irradiation and processing needed
Californium-252	2.6	Multistep irradiation and processing needed
Curium-243	32	Isotopic separation required on product
Einsteinium-254	1.3	Multistep irradiation and processing needed
Europium-152	13	Isotopic separation required High cross section (5000 barns)
Europium-154	16	Isotopic separation required High cross section (1400 barns)
Europium-155	1.7	Isotopic separation required Extremely low (0.03%) fission yield
Gadolinium-162	1	Isotopic separation for a relatively low cross section target

TABLE VI (con't)

Isotope	Half-life years	Reason for Rejection
Krypton-85	10.4	An inert gas
Lead-210	21	Very rare natural isotope from uranium decay 0.005 gram/ton
Osmium-194	2	Target element, Osmium-192 extremely rare
Plutonium-236	2.9	Product isotopic separation required
Plutonium-241	13	Isotopic separation required
Radium-228	6.7	Very rare natural isotope from thorium decay 0.0043 grams/ton
Ruthenium-106	1	Chemistry of this rare metal is extremely complex
Samarium-151	80	Cross section high (12,000 barns) Isotopic separation required
Thulium-171	1.9	Isotopic separation needed for target
Tin-121	5	Isotopic separation for both target and product required
Tritium	12.3	Too costly per watt

TABLE VII

CHARACTERISTICS OF 8 ATTRACTIVE RADIOISOTOPE HEAT SOURCES

	Cobalt 60	Strontium 90	Cesium 137	Promethium 147	Thorium 278	Uranium 232	Plutonium 238	Curium 244
Specific power watts/g	17.4	0.95	0.42	0.41	170	4.4	0.56	2.8
Half-life years	5.3	28	30	2.5	1.9	74	89	17.6
Isotopic Purity %	10	50	35	95	95	85	80	90
Compound Form	Metal	SrT_1O_3	Glass	Pm_2O_3	ThO_2	UO_2	PuO_2	Cm_2O_3
Active Isotope in Compound %	10	24	16	82	83	75	70	82
Specific power of compound w/g	1.7	0.23	0.067	0.34	141	3.3	0.39	2.3
Power density compound w/cc	15.5	1.16	0.215	2.22	1270	33	3.9	27
Availability	Good	Excellent	Good	Fair	Good	Fair	Excellent	Good
Shielding Requirement	Heavy	Heavy	Heavy	Minor	Heavy	Heavy	Minor	Minor
Biological Hazard	$3x10^{-9}$	$3x10^{-10}$	$5x10^{-9}$	$2x10^{-8}$	$2x10^{-12}$	$9x10^{-12}$	$7x10^{-13}$	$3x10^{-12}$
Estimated cost $/watt	33	45	63	168	40	350	1600	<1600
Estimated cost $/gm	570	43	26	68	6600	1540	880	<4300

TABLE VII (con't)

	Cobalt 60	Strontium 90	Cesium 137	Promethium 147	Thorium 278	Uranium 232	Plutonium 238	Curium 244
Curies per gram	1130	142	87	972	4100	114	17	84
Curies per watt	65	149	209	2400	24	26	30	33
Density of compound g/cc	8.9	3.8	3.2	6.6	9	10	10	11.8

TABLE VIII

STRONTIUM TITANATE PROPERTIES

Activity Concentration	33 curies per gram SrT_1O_3
Isotopic Composition	55% ^{90}Sr, 43.9% ^{88}Sr, 1.1% ^{86}Sr ^{88}Sr and ^{86}Sr are stable
Specific power	0.223 watt per gram of SrT_1O_3 6.772 watt per Kilocurie of ^{90}Sr
Thermal energy	148 curies/thermal watt
Density	5.0 gram/cm^3 theoretical 3.7 gram/cm^3 measured
Expansion coefficient	1.12×10^{-5}/°c
Melting point	1900 °c
Mechanical strength	Fair
Thermal stability	Good
Radiation Stability	Good
Thermal conductivity	0.0153 cal/sec·cm·°c
Power density	0.825 watt/cm^3
Gas evolution in decay	None
Vapor pressure	No data
Thermal shock resistance	Good
Burnup characteristics	Dispersibility poor
Capsule compatibility	Excellent with stainless steel and Hastelloy C
Leach rate	1 μ gram/cm^2 day

RADIOLOGICAL AND SAFETY CRITERIA

With the initiation of the atomic age on a rather adverse note, the public has tended to associate nuclear power with nefarious uses. Despite an excellent safety record and intense public indoctrination, nuclear power still has public acceptance problems, and as such, all current and existing atomic power sources are "overdesigned" to the fact that the radiation hazard is truly miniscule. It is because of two factors that the radiological protection system has an added safety factor of two, namely; the Coast Guard is new to this field of endeavor and the extra shielding would aid in ease of acclimation; and with the huge potential of other Coast Guard needs, some 4,000 powered buoys and numerous remote lighthouses, this mollifying of the public could initiate quick acceptance of this specific program.

Before a detailed study of shielding criteria, it is well to review the forms of radiation to be expected from this selected radioisotope. Actually the daughters in the decay chain must also be considered, but as noted in Figure 1, the entire Strontium-90 decay series is composed of beta and bremsstrahlung radiation. These radiation processes may be described as follows.

Beta Radiation

An electron and a neutrino are emitted in beta decay simultaneously from the nucleus of the atom, with the sum of the energies of the two emissions being equal to the total beta

decay energy for the transition. As would be expected, the amount of energy carried off by either particle varies from zero to almost the entire beta decay energy, with the particles forming a continuous energy spectrum and the maximum particle energy being virtually equal to the beta decay energy. For all practical purposes, the neutrino can be neglected, as it is of no practical concern in biological or heat generation calculations; naturally the beta particle is important due to its biological and heating effects.

There are two different forms of beta transitions based on spin and parity changes. These transitions being classified as: "allowed", involving a spin change of 0 or 1, and no parity change (0 or 1, no); with the "unique first forbidden" involving a spin change of 2 and a change of parity (2, yes).

For the beta particles, the shape of the energy spectrum depends on several factors; the decay energy, the transition type, and the atomic number of the emitting nucleus. Obviously the shape of this spectrum is critical to radiation and shielding calculations for determining the particle energy for heat generation calculations, and determination of the bremsstrahlung spectrum.

A theoretical derivation of the number of betas and their energies was presented by Arnold (43) and can be briefly related as:

For allowed transitions

$$P(E) = K\eta W F(Ze,W)(E_o - E)^2 \qquad [7]$$

where:

$P(E)$ = relative number of betas

W = total beta energy in rest mass units

$$= \frac{E(\text{in Mev})}{0.511} + 1 \quad [8]$$

$$\eta = \text{beta momentum} = \sqrt{W^2-1} \quad [9]$$

K = an arbitrary constant

Z_e = atomic number of emitting nucleus

$F(Z_e,W)$ = Fermi Differential Function

The National Bureau of Standards has further defined the Fermi Differential Function to be

$$F(Z_eW) = f(Z_p,\eta)/\eta^2 \quad [10]$$

which can be further defined as

$$f(Z_p,\eta) = \eta^{2+2s}\, e^{\pm\pi\delta}\, [\Gamma(1+s+i)] \quad [11]$$

where:

Z_p = atomic number of particle nucleus

$$s = \sqrt{1-\gamma^2}\ -1 \quad [12]$$

$$\gamma = Z_p/137.0 \quad [13]$$

$$\delta = \gamma/(\eta(1 + n^2)) \quad [14]$$

$\pm$ = beta (-) or positron (+) emission

Γ = standard gamma function

For the unique first forbidden transitions, the expression expands to

$$P(E) = K\eta WF(Z_e,W)(E_o-E)^2\ [\eta^2 + (W_o-W)^2] \quad [15]$$

Resolution of these formulas reveals the average beta energy to be approximately one-third the maximum energy; this can be expressed as

$$\bar{E} = \left(\sum_{E=0}^{E_o} EP(E)\right) / \left(\sum_{E=0}^{E_o} P(E)\right) \qquad [16]$$

Both the Strontium-90 and Yttrium-90 beta spectrum are plotted in Figure 4.

For beta radiation, a rough but useful range determination in air has been calculated by Featherer to be R = 0.593E - 0.160 for E between 0.5 and 2.3 MEV, and R in gm/cm^2 (51).

Bremsstrahlung Radiation

The acceleration or deceleration of an electron results in the emission of a part of its energy through electromagnetic radiation. This can result from two events; first as an electron leaves the nucleus (inner bremsstrahlung) and when it is absorbed (external bremsstrahlung). Here again the spectral distribution will vary from zero to the maximum beta energy, but the majority of energy is released as less energetic radiation. Inner bremsstrahlung has proven to be very small for even the most energetic electrons and hence can be neglected. However, external bremsstrahlung increases with larger beta energies, and increasing atomic number of the absorber. A rough estimation of the energy loss by radiation to that by ionization is

$$\frac{E_{rad}}{E_{ion}} = \frac{Z_a E}{800} \qquad [17]$$

where E is the energy of electron in MEV. It should be noted that the value is somewhat inaccurate for low energy electrons but is considered satisfactory since the absorption of low

energy bremsstrahlung from low energy electrons is quite high. The total bremsstrahlung energy is found by dividing the beta spectrum into energy groups and noting subsequent energy emission. This calculation gives the total energy but is not designed to give an energy spectrum; however, the total beta energy equals the total bremsstrahlung energy.

A review of equation [7] indicates that a few percent of the beta energy will escape as bremsstrahlung and this would not be recoverable as heat within the source. As maximum heat recovery is desired, the source is encapsulated in Hastelloy C having a thickness equal to one-tenth the maximum range of the beta ray--thus some of the escaped energy will be recaptured. Self-absorption would reduce the escaping bremsstrahlung to considerably less than the total bremsstrahlung produced; but a review of self-absorption criteria from Strontium-90 reveals satisfactory operation for the size of the generator in question. The total bremsstrahlung energy release per beta emission is thus important for heat sources and is given in Tables IX and X for Strontium-90 and Yttrium-90 respectively.

A formula expressing the energy radiated is

$$I = C[4(1 - \frac{K}{E}) + 3\frac{K}{E} \ln \frac{K}{E}] \Delta K \qquad [18]$$

where:

I = radiated energy

C = arbitarary constant

E = kinetic beta energy

K = energy of bremsstrahlung photons

Summing over all K will yield the total energy radiated. Now the bremsstrahlung spectrum, $S(K)$, can be evaluated by the expression

$$S(K) = \sum_{E=0}^{E_o} \left[\frac{EP\ (E)}{\Sigma EP\ (E)}\right] \left[\frac{Z_a E}{Z_a E + 800}\right] \left[\frac{1}{1.25}\right] [I] \qquad [19]$$

where $\Sigma EP\ (E)$ is from $E=0$ to $E=E_o$ and the formula is composed of three factors: the fraction of total beta energy at E; the fraction of this energy lost by radiation; and the fraction of radiated energy which has energy K. This then yields the number, $N(K)$, of energy K per ΔK proton energy interval per beta emission.

$$N(K) = S(K)\ \bar{E}/K \qquad [20]$$

A computer program to summarize all these results from all shielding materials has been established and presented in Arnold (43). Also Figure 6 displays the shielding properties of Iron, Lead, and Uranium, the practical shielding materials for Strontium Titanate.

Now that the nature of the radiation to be experienced is understood, it is possible to review the safety criteria.

Formal safety has evolved since the initial Manhattan Project of 1943, and the factors which determine safety hazards may be listed as follows:

1. relative biological effectiveness
2. energy of radiation
3. tissue involved
4. total dose

5. dose rate

6. body area exposed

7. internal or external exposure

As would be expected, there are numerous criteria for safety as established by federal, state, and local authorities; here I will rely on the National Bureau of Standards publications for promulgated maximum permissible exposure and other criteria. It should be noted that the buoy is stationed at the twelve mile limit, solely because that is the furthest extent of Atomic Energy Commission licensing capability and jurisdiction. The Atomic Energy Commission safety criteria are established by Section 20 of Title 10 of the Code of Federal Regulations.

At this point it is useful to define current radiological units

1. Roentgen - absorption of 83 ergs/gm of air from X-ray or γ-ray

2. Rad - absorption of 100 ergs/gm

3. RBE - relative biological effectiveness - based on the biological effects of radiation with the X-ray establishing the base of 1.

4. Rem - (roentgen equivalent man)--RADS x RBE--produces biological effect of 1 roentgen but not entirely from X-ray or γ-ray.

With beta rays having a RBE of 1, the maximum permissible exposure to ionizing radiation was established to be 100 mrad/ week to eyes, blood forming organs, and gonads of persons 18

years and older. This age factor was subsequently redefined in the exposure rating of

$$D = 5(N - 18) \qquad [21]$$

where:

D = absorption in rems

N = age of worker

It should be noted that this maximum rate can be safely averaged over a several months period, but if truly long periods (over 13 weeks) are involved the current practice is to reduce this exposure by a factor of ten. Other notable exceptions are: up to 125 rem for hands, forearms, feet, and ankles; up to 25 rem emergency overdose allowed once in a lifetime; a whole body dose of 1.25 rems/quarter; total skin dose of 7.5 rems/quarter; maximum spot contamination of 1 rem per 2 cm^2 of exposed body surface; however, if ingested or inhaled

$$MPC = \frac{aqfo}{TB(1-e^{\frac{0.693t}{T}})} \qquad [22]$$

where:

MPC = maximum permissible concentration in body in millicuries/cc of air or water

q = total body burden

fo = fraction of radioactivity remaining in body/total body radiation received

B = original radiation arriving at organ

T = half-life

t = time duration

$a = 3.5 \times 10^{-8}$ for air

3.11×10^{-4} for water

In fact, q has been further defined as

$$q = \frac{5.6 \times 10^{-5}\ mW}{fo\ \Sigma\ E(RBE)N} \qquad [23]$$

where:

RBE = in rads

M = mass of affected organ

W = permissible mrad/week

E = disintergration energy (in Mev)

N = non-uniform distribution factor

= 5 for bone

= 1 for all other tissue

Applying this above equation to Strontium-90 has yielded the following maximums:

1. $8 \times 10^{-7}\ \frac{\mu ci}{m\ell}$ in water
2. $2 \times 10^{-10}\ \frac{\mu ci}{m\ell}$ in air

These formulas, although accurate, tend to mask the fact that the biological danger to radiation is very significant for Strontium-90, which is classified as one of the four most hazardous radioisotopes; mainly because of its strong internal hazard, especially to bone, as it has a very strong affinity to that specific tissue.

Current Atomic Energy Commission practice has limited the maximum shield surface rate to be 5.0 mr/hr, and in an attempt to promote safety as noted earlier; the buoy power

generator outer shield was designed for half of that--2.5 mr/hr. Tests have established background radiation to be only 0.05 mr/hr. If source storage facilities are provided by the buoy maintenance facilities, the limit of radiation detectable at a range of one foot from the source is 5 mrem/hr. Likewise before buoy deployment and later overhaul, two survey tests are recommended, namely;

1. The Wipe Test - a one hundred square centimeter smear of the outside shield connection surface. This smear should then be monitored for excess activity above allowed limits.
2. Air Activity - a LAS-1 air sampler is utilized to measure air activity around the sample. Again, excess activity would indicate a source failure.

In addition to the above tests, certain on-station procedures should insure adequate safety. This involves wearing a monitor badge if within seven feet of the source and using E-500B beta survey meters when operations are in progress. It would also be advisable to have the following for decontamination purposes; a saturated solution of Potassium Permanganate and 0.2 N sulfuric acid, and/or sodium acid sulfite.

Safety in any endeavor should be a primary goal, and especially so in the nuclear field because of the potential hazard. This isotope generator as designed shieldwise is some 50% above the established Atomic Energy Commission and National Bureau of Standards minimum criteria. As

Strontium Titanate is insoluble in liquids, the application of safety procedures and precautions listed here should make the beta and bremsstrahlung radiation hazard low; and be a very positive factor in the acceptance of this design.

In summarizing the safety criteria, it is important to reemphasize that the Atomic Energy Commission and National Bureau of Standards have promulgated a code of safety criteria which will be adhered to in this design. The extreme biological hazard of Strontium-90 has led to the adoption of an added safety factor of 2 in the outer shield dose rate, as the beta and bremsstrahlung radiation create a severe internal hazard. When handling the source, both film badges and E-500B meters should be used, with wipe tests and air samplers used to check the generator itself for leaks. In general however, the selection of Strontium Titanate for this application has greatly reduced the potential radiation hazards.

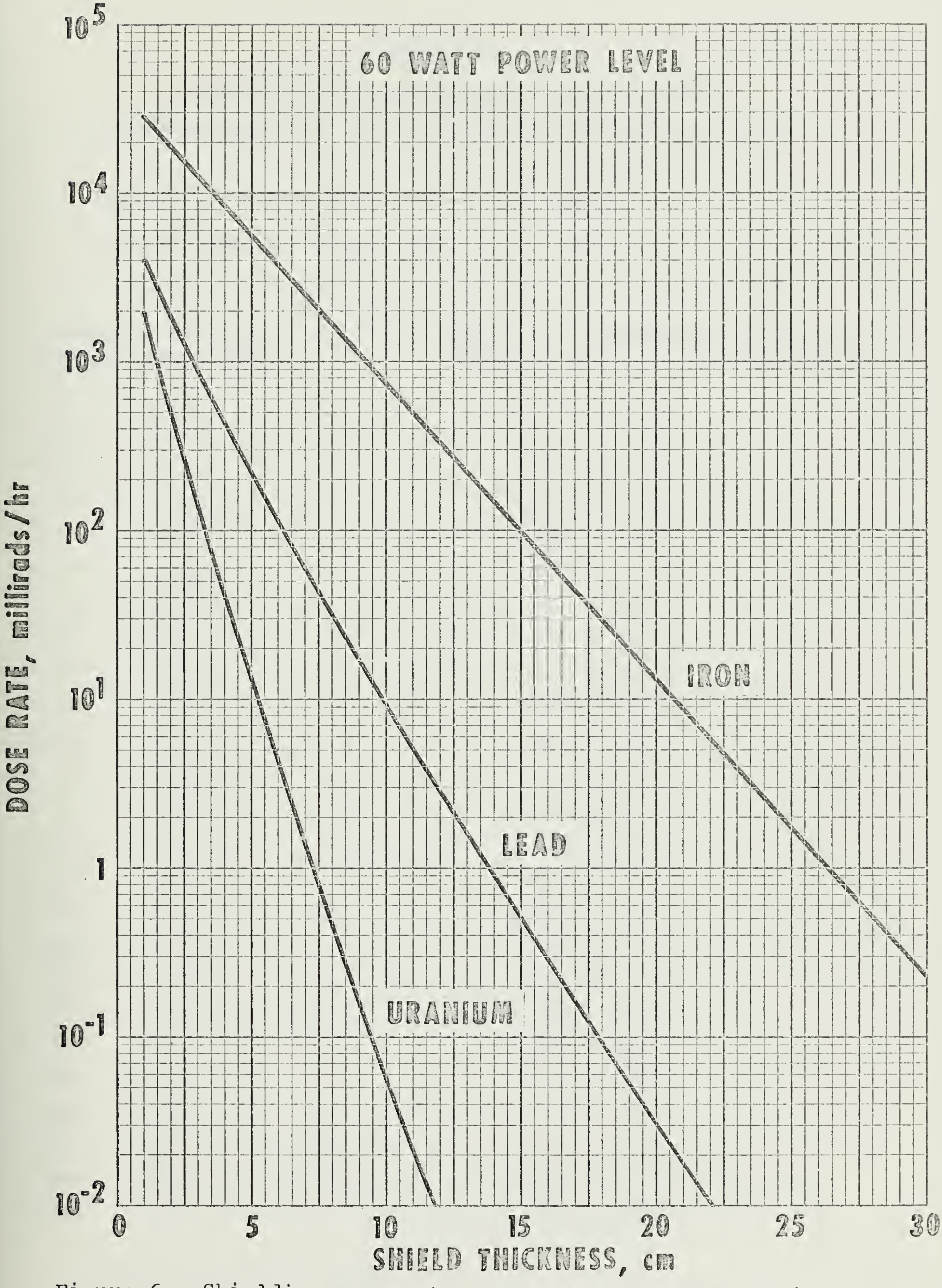

Figure 6 - Shielding Properties of Lead, Iron, and Uranium

TABLE IX

PRODUCTION OF BREMSSTRAHLUNG PHOTONS FROM
STRONTIUM-90 BETA IN STRONTIUM TITANATE MATRIX (43)

Maximum Beta Particle, MEV	0.545
Average Beta Particle, MEV	0.201

Bremsstrahlung Energy Group (MEV)		Number of Photons per Beta Particle within ΔE Energy Group
0.020	± 0.01	1.009×10^{-2}
0.040	± 0.01	4.004×10^{-3}
0.060	± 0.01	2.195×10^{-3}
0.080	± 0.01	1.348×10^{-3}
0.100	± 0.01	8.845×10^{-4}
0.120	± 0.01	6.034×10^{-4}
0.140	± 0.01	4.217×10^{-4}
0.160	± 0.01	2.993×10^{-4}
0.180	± 0.01	2.141×10^{-4}
0.200	± 0.01	1.537×10^{-4}
0.220	± 0.01	1.103×10^{-4}
0.240	± 0.01	7.851×10^{-5}
0.260	± 0.01	5.571×10^{-5}
0.280	± 0.01	3.895×10^{-5}
0.300	± 0.01	2.678×10^{-5}
0.320	± 0.01	1.801×10^{-5}
0.340	± 0.01	1.179×10^{-5}
0.360	± 0.01	7.448×10^{-6}
0.380	± 0.01	4.497×10^{-6}
0.400	± 0.01	2.559×10^{-6}
0.420	± 0.01	1.345×10^{-6}
0.440	± 0.01	6.333×10^{-7}
0.460	± 0.01	2.534×10^{-7}
0.480	± 0.01	7.807×10^{-8}
0.500	± 0.01	1.472×10^{-8}

TABLE IX (con't)

Bremsstrahlung Energy Group (MEV)		Number of Photons per Beta Particle within ΔE Energy Group
0.520	± 0.01	7.336×10^{-10}
0.540	± 0.01	0.000

Total Bremsstrahlung Energy, MEV/Beta particle 9.924×10^{-4}

TABLE X

PRODUCTION OF BREMSSTRAHLUNG PHOTONS FROM YTTRIUM-90 BETA IN STRONTIUM TITANATE MATRIX (43)

Maximum Beta Particle, MEV	2.27
Average Beta Particle, MEV	0.944

Bremsstrahlung Energy Group (MEV)		Number of Photons per Beta Particle within ΔE Energy Group
0.100	± 0.05	4.537×10^{-2}
0.200	± 0.05	1.782×10^{-2}
0.300	± 0.05	9.456×10^{-3}
0.400	± 0.05	5.665×10^{-3}
0.500	± 0.05	3.613×10^{-3}
0.600	± 0.05	2.389×10^{-3}
0.700	± 0.05	1.611×10^{-3}
0.800	± 0.05	1.098×10^{-3}
0.900	± 0.05	7.493×10^{-4}
1.000	± 0.05	5.092×10^{-4}
1.100	± 0.05	3.425×10^{-4}
1.200	± 0.05	2.264×10^{-4}
1.300	± 0.05	1.460×10^{-4}
1.400	± 0.05	9.110×10^{-5}
1.500	± 0.05	5.434×10^{-5}
1.600	± 0.05	3.050×10^{-5}
1.700	± 0.05	1.576×10^{-5}
1.800	± 0.05	7.220×10^{-6}
1.900	± 0.05	2.764×10^{-6}
2.000	± 0.05	7.850×10^{-7}
2.100	± 0.05	1.239×10^{-7}
2.200	± 0.05	3.540×10^{-9}

Total Bremsstrahlung Energy, MEV/Beta Particle 2.078×10^{-2}

THERMOELECTRIC GENERATOR DESIGN

With the radioisotope definitely selected and a thorough knowledge of its decay scheme, it is now possible to design the three major components of the generator system: the isotope sizing and encapsulement, the power conversion system, and the biological shield. To initiate this design it is first advantageous to list the desired goals, as the final must be a compromise among these,

1. maximum reliability
2. minimum system cost
3. minimum space, weight, and interfaces
4. maximum radiation resistance
5. maximum structural integrity
6. compatability with environment
7. maximum safety
8. minimum radiation hazard

With these goals established, it is now desirable to establish a means of heat-to-electricity conversion, and there are four possible direct conversion systems, to the author's knowledge,

1. Conversion of fluorescent light
2. Generation of P-N junction semi-conductors ion pairs--thermoelectric
3. Magnetohydrodynamic
4. Collection of charged particles in retarding field--thermionic

Of this list only two--thermionic and thermoelectric--can be built to withstand the shocks, vibrations and harsh environment of a marine environment as they are rugged and have no moving parts, and as the others are extremely vibration sensitive. All such conversion systems are extremely inefficient with the maximum efficiency being eleven percent for the thermionic; however, a high operational temperature of some 1100 degrees Fahrenheit eliminates the thermionic from consideration. Thus the rugged, yet less efficient thermoelectric system must be employed and be optimumly applied.

Briefly the thermoelectric process may be described as follows: the radiation is absorbed in the source and containment material where the beta and bremsstrahlung energy is transformed to heat; then the application of P-N type semiconductors converts the heat to electrical power. This output is "power flattened" and stored in nickel-cadmium batteries under the trickle charge principle. The batteries then supply the desired direct current power as needed. The actual amount of Strontium-90 for a five year on-station power of fifty-six watts was calculated utilizing the maximum five percent efficiency of cascaded thermoelectric material. The right circular cylinder form was selected as it most nearly resembled the normal buoy counterweight, and a computer program calculated the desired dimensions. These dimensions were then checked for self-absorption losses and satisfactory results noted. It should be noted that the size calculated was not of the

standard Strontium Titanate pellet form; however, the fuel could easily be manufactured in these dimensions if there was sufficient demand. Next the encapsulement material was selected. The following are criteria deemed important for the encapsulement material.

1. No brittleness from radiation
2. Little diffusion at operating temperatures
3. Little or no corrosion
4. No oxidation
5. Good mechanical properties at high temperatures
6. High temperature stability
7. Good thermal conductivity
8. No brittleness from welding
9. Little microporosity
10. Relatively inexpensive
11. Not difficult to machine

There are numerous potential containment materials such as:

1. Molybdeum	7. Tanlatum
2. Tungsten	8. Monel K 500
3. Niobium	9. Inoconel 600
4. Platnium	10. Hastelloy C, X, or F
5. FS-85 steel	11. TZM
6. Stainless steel	12. TD Nickel

The final selection was between stainless steel and Hastelloy C as both had a maximum combination of the desired properties; however, the final selection was a 0.25 inch

Hastelloy C encapsulement as it had had earlier successes in the SNAP 7C and 7D programs. Hastelloy C is considered extremely reliable from earlier experimental work, especially in conjunction with Strontium Titanate. A second 0.25 inch Hastelloy C plate then acts as the one-tenth thickness needed to effectively and efficiently slow all beta and bremsstrahlung radiation; this is normally defined as the hot shoe. An epoxy resin is applied between the two Hastelloy C shields to electrically isolate the fuel capsule from the hot shoe. The P-N type thermoelectric semi-conductors are then attached to this second plate. This sequence is graphically displayed in Figure 10. Then all remaining exposed Hastelloy C surface areas are covered with an asbestos sheet to reduce thermal losses.

The thermoelectric effect is a phenomena first described by Seebeck in 1832, who defined the following equation for current produced between the junction of two dissimiliar metals,

$$Z = \frac{a^2}{pK} \qquad [24]$$

where:

Z = figure of merit

K = thermal conductivity in w/cm

a = Seebeck effect constant in volt/°c

p = electrical resistivity in ohm-cm

The value Z is normally combined with T, the temperature, when rating the effects of semi-conductors. Several P-N semi-

conductors are compared in Figures 8 and 9. In these figures, the Strontium Titanate fuel will operate in the hot junction temperature range of 600 ±50°F, hence this is the design selection temperature of the semi-conductor. The temperature range and reliability tend to favor either lead-telluride or germanium-silicon thermocouples; however, it has been experimentally noted that cascaded lead-telluride elements seem to work best with Strontium Titanate in this power range (60 watts), and yield the maximum efficiency of five percent. The following alterations to the lead-telluride semi-conductors tend to improve both their effectiveness and average lifetime, this being; the N-type conductors, in which the electrons diffuse to the cold ends, are doped with a 1% bismuth coating; while the P-type conductors, in which the unfilled electron "positions" move to the hot ends, are doped with a 3% sodium coating. Physically these semi-conductors come in pairs called shoes, which are 1.0 by 1.25 inches and have a voltage output of 0.5 volt per set. Thus some 26 shoe pairs are needed to produce the twelve volts of desired power. These shoes are symmetrically placed about the periphery of the Hastelloy C capsule material to convert the heat to electrical power. To insure a maximum efficiency, an iron spherical washer, spring, and snap ring assembly is inserted between the shoes and the lead biological shield to insure constant, thermal contact to the absorber material.

These semi-conductors are physically connected in series through a static converter to stabilize the direct current output and a voltage regulator in order to prevent overcharging and battery gassing. This current is then used to trickle charge the nickel-cadmium batteries. A typical isotope power electrical spectrum is presented in Figure 7. The twelve nickel-cadmium batteries themselves are split into a series--parallel combination with two six-cell series paralleled for optimum useage.

There is a resistance backing material surrounding this portion of the generator to protect the actual inner system from chemical attack, and provide insulation. Many materials such as polyethylene, teflon, and glass could be used, but such factors as weakness under strong caustic solutions favors the selection of a new material, Min-K, developed by the Johns Manville Company strictly for this purpose. Previous successes in the early SNAP series tend to affirm this selection.

Now the combination biological shield and heat sink must be designed. As expected this outer covering is extremely important for two reasons; first as the relatively inefficient thermoelectric processes leave large unused quantities of heat, which must be led away, or the fuel could easily reach its melting point and fail. The total weight of the containment material insulation, and thermoelectric shoes is calculated to be 1,050 pounds.

Spaced taps from the inner Hastelloy C shield metal are attached to the biological shield such that the unwanted heat is dissipated through the outer shield to the surrounding seawater. The biological shield also functions as the primary shielding device to restrict the harmful beta and bremsstrahlung radiation. As noted earlier, an overly designed safety system was selected with the conservative outer shield radiation rate of 2.5 mr/hr. Using tabulated values of Strontium Titanate from Arnold (43), three attractive shield metals were reviewed--Iron, Lead, and Uranium. The Lead was finally selected for two reasons: it provides the approximate weight needed for the buoy counterweight for naval architecture stability; and it is one of the more effective shielding metals. Some 13.3 cm was found to be adequate lead shielding for this purpose. The outer periphery of the lead shield is then sprayed with aluminum oxide to reduce potential seawater corrosion. Cutaway views of the entire generator are presented in Figures 11 and 12. The previously mentioned computer program forms Tables XII and XIII. This generator is then bolted to the counterweight tube and the electrical connections made to the batteries, and voltage and current regulators in the buoy body. This bolt-attachment-assembly allows two important aspects; first the buoy body and navigational aids subsystem can be owned and maintained by the Coast Guard; while secondly, the thermoelectric generator device may be manufactured in its entirity at the isotope production facility and shipped to the Coast Guard for easy installation. This system provides for a

limited handling and minimum of radiation accidents. Likewise, if a larger demand is subsequently made for these devices, it will be in a standard easily produceable form. A summary of the thermoelectric generator characteristics is presented as Table XI.

As designed, the generator should prove extremely reliable and effective; however, the following potential problems have been noted on earlier similar prototypes--all of which are related to high temperature effects.

1. Spalling of fuel capsule
2. Release of caustic sulfur from Min-K insulation
3. Reduction of sodium hence loss of P-type semi-conductor efficiency
4. Oxidation of copper in wiring
5. Spalling of iron semi-conductor holders

It should be noted that any isotope design must be experimentally tested by the Atomic Energy Commission before a license will be issued to provide radioactive materials. This has resulted in a high success rate for this form of power systems.

This design has benefitted from the earlier SNAP 7 series experiments and subsequent technological advances, and as designed should not only prove readily adaptable to this buoy system, but should prove a reliable, efficient system for its five year on-station time.

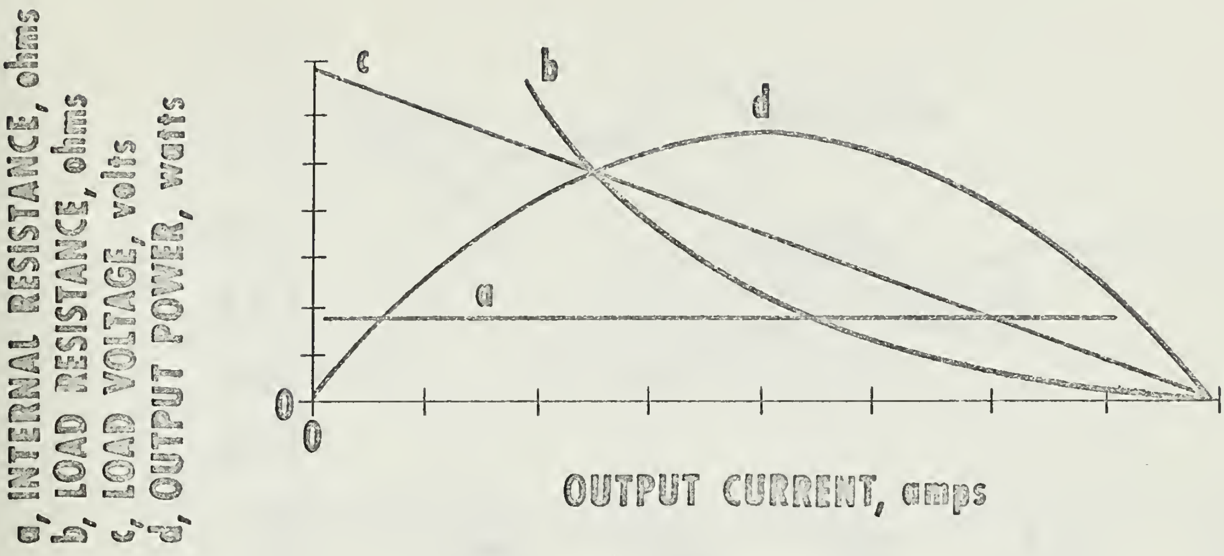

Figure 7 - Isotope Electrical Output Spectrum

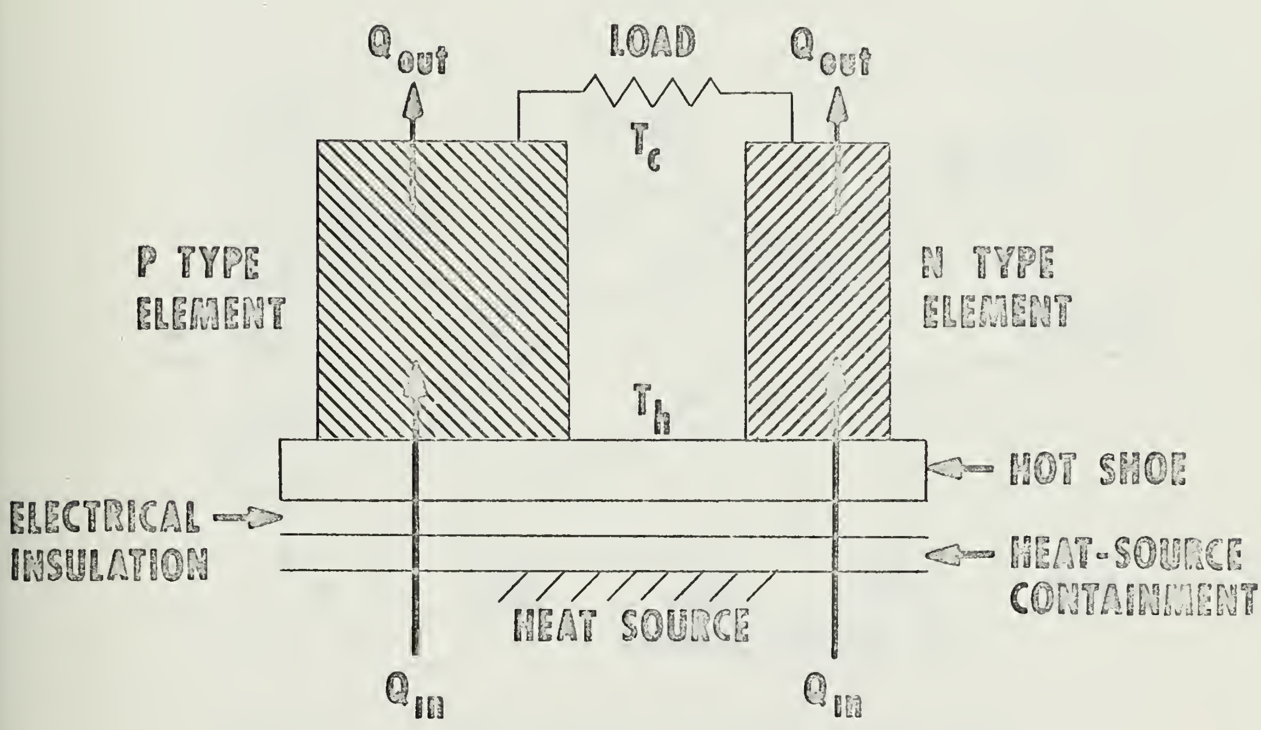

Figure 10 - P-N Semi-conductor Effect

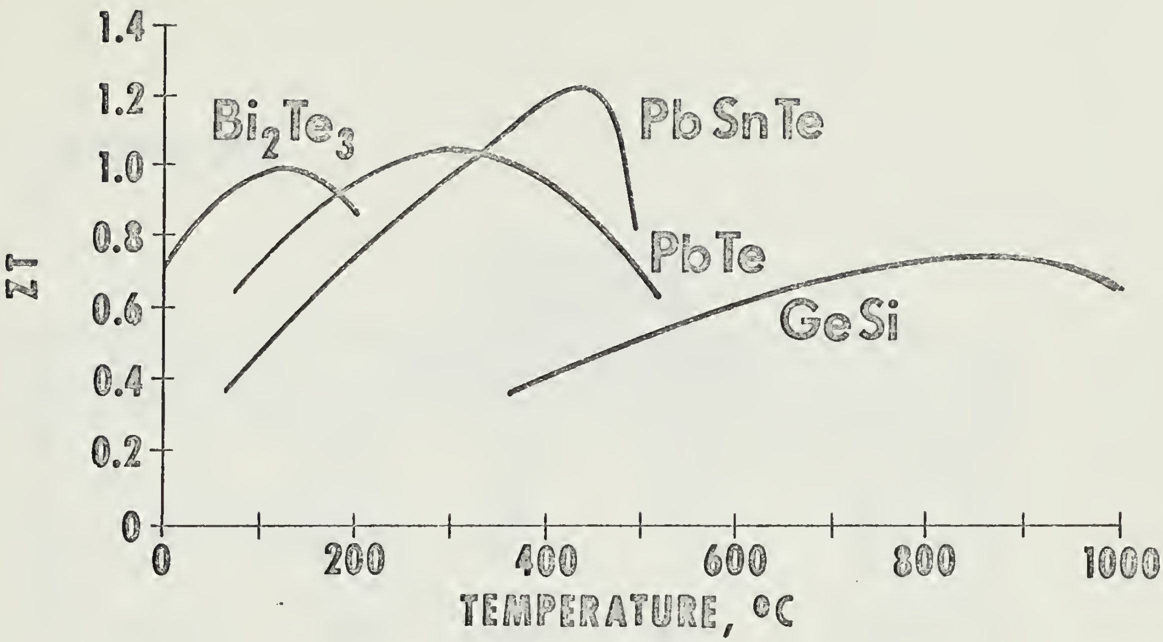

Figure 8 - N-Type Semi-Conductor Properties

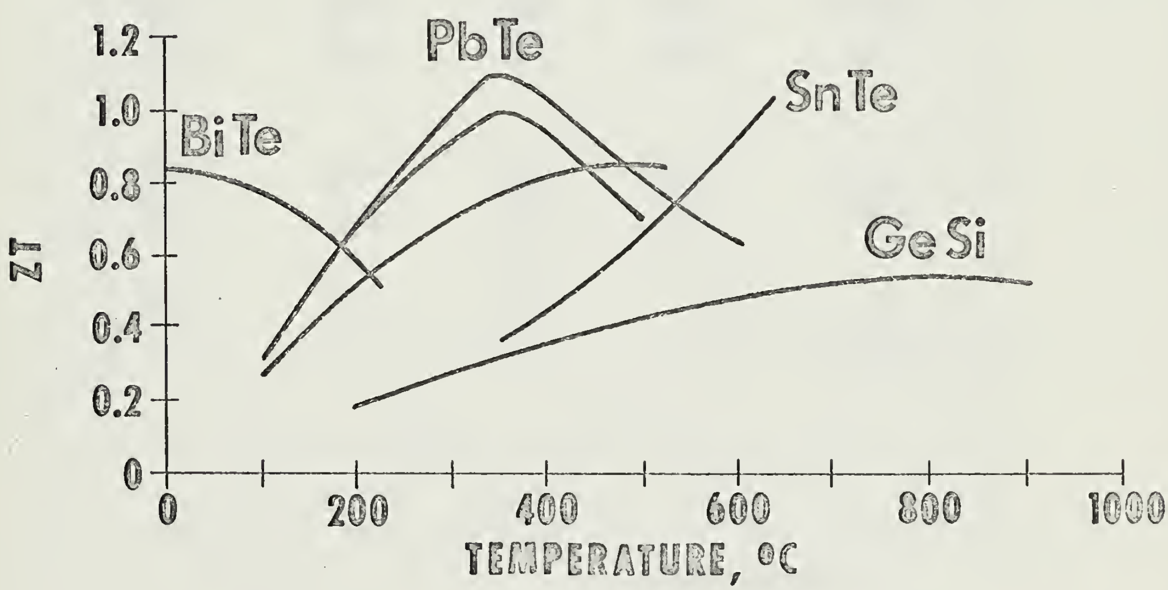

Figure 9 - P-Type Semi-conductor Properties

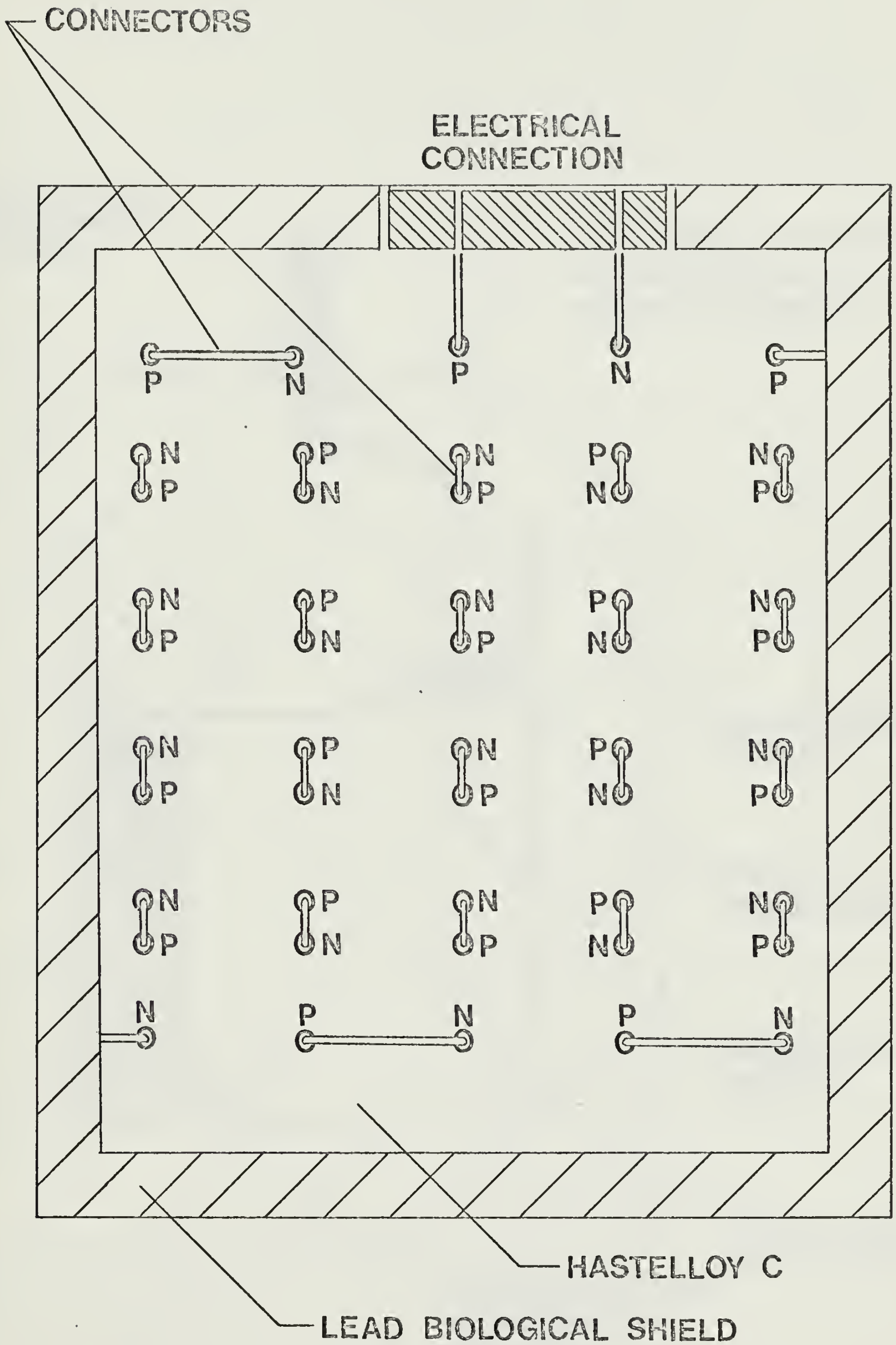

Figure 11 - Cutaway View of Semi-Conductor Arrangement

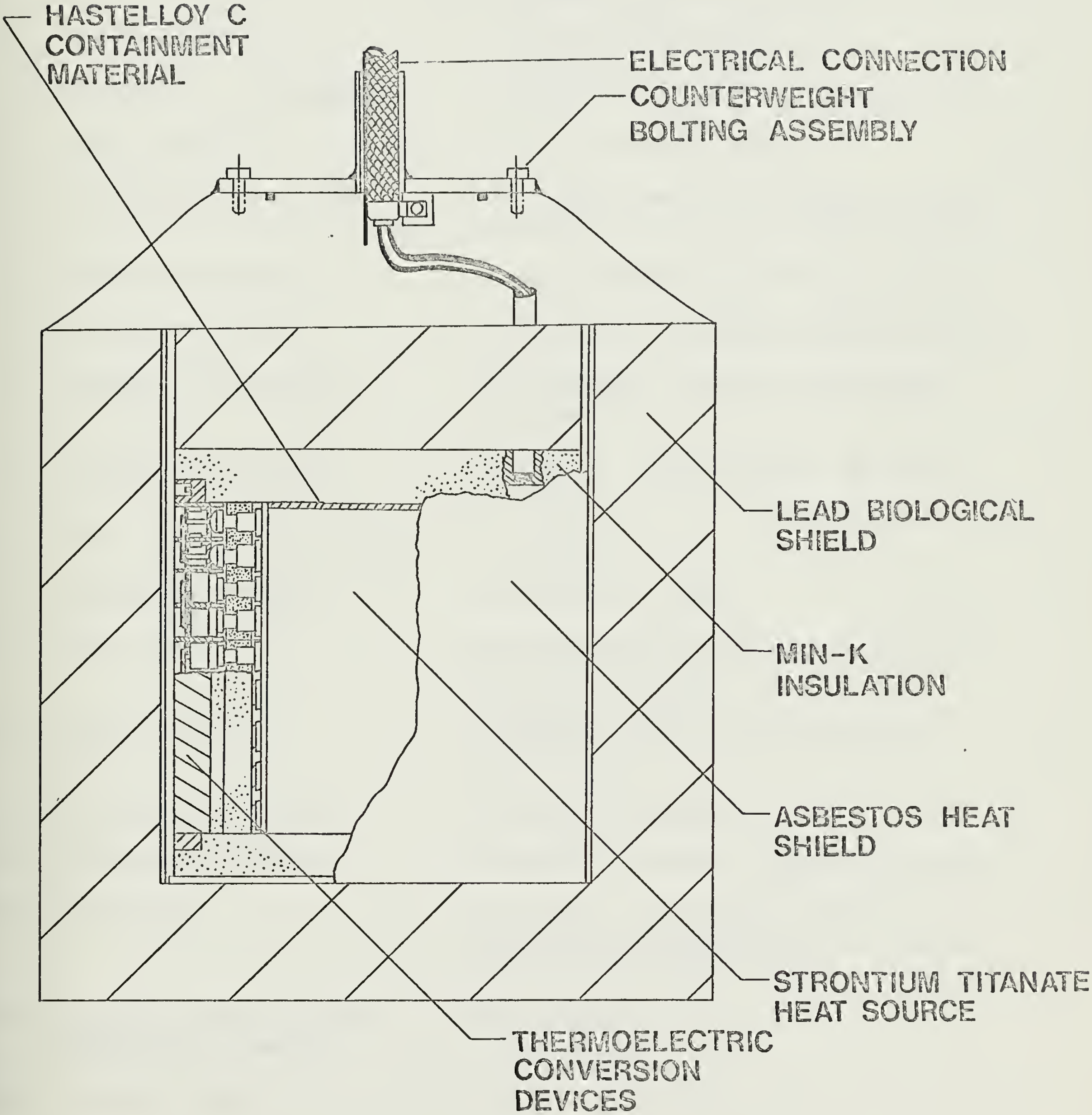

Figure 12 - Cutaway View of Thermoelectric Generator

TABLE XI

SUMMARY OF THERMOELECTRIC GENERATOR AND ELECTRICAL SYSTEM CHARACTERISTICS

1.	Fuel	Strontium Titanate in right circular cylinder form
2.	Encapsulement	0.25 inch Hastelloy C
3.	Electrical Insulation	Coating of resistant epoxy resin
4.	Heat shield	0.25 inch Hastelloy C
5.	P-N Semi-conductors	26 "shoe" sets, 0.5 volt per set surface area of 1.25 in^2 per set
6.	P-type material	Lead telluride doped with sodium
7.	N-type material	Lead telluride doped with bismuth
8.	Maximum efficiency	In cascaded series with copper wiring, 5%
9.	Thermal insulation	Asbestos strip backed by Min-K packing
10.	Outer shield dose rate	2.5 mr/hr
11.	Biological shield	13.3 cm of lead
12.	Heat sink	The biological shield dissipates heat to seawater
13.	Outer coating	Aluminum oxide for corrosion protection
14.	Voltage protection	Voltage regulator
15.	Current protection	Static converter, power flattener
16.	Batteries	12 unit cell nickel-cadmium, trickle charged wired in 2 sets of 6 series parallel
17.	Expected hot junction temperature range	604-650°F
18.	Voltage range	13.0 - 12.0 volt D.C.

TABLE XI (con't)

19.	Current range	To 2.5 amps
20.	Power range	56.0 to 63.6 watts
21.	Seawater temperature	45°F
22.	On-station life	5 years
23.	Attachment to buoy	By bolting generator to counterweight tube

TABLE XII

THERMOELECTRIC GENERATOR DESIGN COMPUTER STUDY

This simple thermoelectric generator computer study is based on the physical constants of the fuel, Strontium Titanate; and shielding, Lead, as denoted by Arnold in his text on isotopic shielding requirements (43). Basically, the program is evolved in two parts: first, manipulation of Arnold's constants to get the desired fuel loading; and second, the use of the right circular cylinder formula to establish the component, and final generator design, where

Height = 2 x Radius

and

Volume = π x Radius Squared x Height

The right circular cylinder shape was selected to create the generator in the compact form necessary to function as the counterweight for buoy stability purposes.

The computer design results meet all radiation and structural criteria previously established in an efficient buoy counterweight form.

```
$JOB            JOB1,KP=29,TIME=1,PAGES=50
      WRITE(6,50)
   50 FORMAT(10X,'RADIOISOTOPE SHIELDING AND POWERING CALCULATIONS'//
     110X,'STRONTIUM TITANATE IS THE ISOTOPIC FUEL'//
     210X,'LEAD IS THE SHIELDING METAL'//
     310X,'THE THERMOELECTRIC GENERATOR IS CYLINDRICAL'//
     410X,'GENERAL REFERENCE--F.D. ARNOLD, SHIELDING HANDBOOK'/////)
      WATT=63.6
      POWDEN=0.85
      EFFIC=0.05
      EFFDEN=3.8
      ACTIV=126.0
      OVEFF=EFFIC*100.
      CURIE=ACTIV*WATT/(POWDEN*EFFIC)
      WGTISO=CURIE*EFFDEN/ACTIV
      POWR=56.0
      WRITE(6,40)  POWR,CURIE,OVEFF,WGTISO
   40 FORMAT(10X,'THE POWER NEEDED IS',5X,F6.2,5X,'WATTS'//
     110X,'THE TOTAL CURIES NEEDED ARE',5X,F10.2,5X,'CURIES'//
     210X,'THE OVERALL EFFICIENCY IS',5X,F6.2,5X,'PERCENT'//
     310X,'THE WEIGHT OF STRONTIUM TITANATE IS',5X,F10.4,5X,'GRAMS'////)
      EXPMAX=100./(5.*8.)
      SHTHIC=13.3
      VOLISO=WGTISO/EFFDEN
      RADISO=(VOLISO/(2.*3.14159))**0.333
      HGTISO=2.*RADISO
      DIS=10.0
      UNCOST=0.50
      TOTCOS=UNCOST*CURIE
      HGTSHD=HGTISO+DIS+2*SHTHIC
      RADSHD=RADISO+DIS+SHTHIC
      VOLSHD=3.14159*(((HGTISO+DIS+2*SHTHIC)*(RADISO+DIS+SHTHIC)**2)-
     1((HGTISO+DIS)*(RADISO+DIS)**2))
      DENMET=11.33
      WGTKG=VOLSHD*DENMET
      PBWGT=WGTKG*2.2*0.001
```

Table XII (con't)

```
      WRITE(6,30) EXPMAX,SHTHIC,HGTSHD,RADSHD,VOLSHD,PBWGT,TOTCOS
   30 FORMAT(10X,'MAXIMUM EXPOSURE IS',5X,F6.2,5X,'MR/HR'//
     110X,'SHIELD THICKNESS IS',5X,F6.2,5X,'CM'//
     210X,'HEIGHT OF SHIELD IS',5X,F6.2,5X,'CM'//
     310X,'RADIUS OF SHIELD IS',5X,F6.2,5X,'CM'//
     410X,'VOLUME OF THERMOELECTRIC PACKAGE IS',5X,F9.1,3X,'CC'//
     510X,'WEIGHT OF SHIELD IS',5X,F8.2,5X,'POUNDS'//
     610X,'COST OF ISOTOPE IS',5X,F8.2,5X,'DOLLARS'//)
      WGTOT=1050.
      TOTWGT=WGTOT+(2.2*0.001*(WGTKG+WGTISO))
      TOTHGT=HGTSHD/2.54
      TOTWDE=2*RADSHD/2.54
      WRITE(6,20) TOTWGT,TOTHGT,TOTWDE
   20 FORMAT (10X,'THE TOTAL THERMOELECTRIC GENERATOR PACKAGE FOR'/
     110X,'COUNTERWEIGHT IS',5X,F8.2,5X,'POUNDS'//
     210X,'THE TOTAL HEIGHT OF GENERATOR IS',5X,F8.2,5X,'INCHES'//
     310X,'THE TOTAL WIDTH OF GENERATOR IS',5X,F8.2,5X,'INCHES'//)
      CALL EXIT
      END
$ENTRY
$STOP
```

Table XII (con't)

TABLE XIII

THERMOELECTRIC GENERATOR COMPUTER RESULTS

RADIOISCTOPE SHIELDING AND POWERING CALCULATIONS

STRONTIUM TITANATE IS THE ISOTOPIC FUEL

LEAD IS THE SHIELDING METAL

THE THERMOELECTRIC GENERATOR IS CYLINDRICAL

GENERAL REFERENCE--E.D. ARNOLD, SHIELDING HANDBOOK

THE POWER NEEDED IS 56.00 WATTS

THE TOTAL CURIES NEEDED ARE 188555.10 CURIES

THE OVERALL EFFICIENCY IS 5.00 PERCENT

THE WEIGHT OF STRONTIUM TITANATE IS 5686.5820 GRAMS

MAXIMUM EXPOSURE IS 2.50 MR/HR

SHIELD THICKNESS IS 13.30 CM

HEIGHT OF SHIELD IS 48.97 CM

RADIUS OF SHIELD IS 29.49 CM

VOLUME OF THERMOELECTRIC PACKAGE IS 115361.4 CC

WEIGHT OF SHIELD IS 2875.50 POUNDS

COST OF ISOTOPE IS 94277.56 DOLLARS

THE TOTAL THERMOELECTRIC GENERATOR PACKAGE FOR
COUNTERWEIGHT IS 3938.01 POUNDS

THE TOTAL HEIGHT OF GENERATOR IS 19.28 INCHES

THE TOTAL WIDTH OF GENERATOR IS 23.22 INCHES

BUOY BODY DESIGN

The optimum in outer harbor aids to navigation would be a fixed platform or station, as it would provide not only a spacious, stable platform, but a precisely positioned navigational marker. The costs of such a proposal, however, would quickly eliminate its feasibility or practicality, but the design of a buoy should reflect these austere goals. Physically, the buoy is designed in three steps: first, the entire navigational aid package is devised and properly stationed atop the buoy body; next a counterweight and mooring system of approximately the same total weight as the upper section is attached to the bottom of the buoy body; and then a buoy body is selected to reflect the following goals,

1. Provide damage stability against potential flooding.
2. Have good wave riding characteristics.
3. Provide minimum off the vertical motion for navigational aids, notably the flashing light, which derive maximum usefulness (detection range) operating from the exact vertical position.
4. Support the mooring chain.
5. In riding currents, reduce induced heel to the minimum.
6. Provide sufficient freeboard to protect electronic equipment and battery storage spaces from salt water wash.

There are numerous potential buoy body shapes such as the can, nun, spar, and sphere; however, the only buoy body with years of proven successful operation capable of realizing these goals in deep water service is the circular cross section, spherical-shaped structure. As such, there has been considerable hydrostatic and hydrodynamic testing of the two largest Coast Guard buoys, the 8x26 and 9x38--both of which have spherical buoy bodies (13). Buoy forms, as are ship hulls, must be model tested, and the proper selection of scaling criteria involves a compromise between the Reynold's and Froude's effects. Basically, these two distinct groupings--surface and viscous effects--may be subdivided as follows:

1. Surface effects
    a. Wave forces
    b. Buoyancy
2. Viscous effects
    a. Friction drag
    b. Flow separation

Ideally it is desirable to use both the Froude and Reynold's scaling, as each has a decided effect on ultimate buoy performance; however, studies of model performance have established Froude scaling as embodying the predominate effects, and thus the Reynold's scaling has been safely disregarded. Similarly, such factors as surface tension, cavitation, roughness, and current speed can be included in the scaling allowances, but for buoys, these effects are generally miniscule. Such parameters as size, costs, and model

reliability have been consolidated into the following recommended ratios for buoy studies--geometric scaling, 4 to 1, and Reynold's scaling, 64 to 1. Naturally each buoy design would have to be individually reviewed for unique scaling criteria, but these above mentioned ratios have proven successful in numerous past model studies.

In using these model tests, wave and seaway spectra must be adopted to adequately define the on-station environmental conditions before meaningful tests can be concluded. Certain problems exist when establishing a buoy in moderately shallow water such as the outer Boston Harbor moor (70 feet). There, ocean bottom effects produce elliptical water particle motions, whose effects are illustrated in Figures 13 and 14. The Gerstner and Stokes seaway models are the most attractive of the numerous analytical environmental predictors, with the Gerstner model being particularly applicable to moderate depths. As such, the seventy foot mooring depth of this spherical buoy design could be adequately accounted for by this model's characteristics:

1. restoring force - gravity
2. motion - stationary closed orbits
3. fluid - irrotational and non-divergent
4. phase velocity - g/k
5. profile - trochoidal
6. type solution - exact
7. steepness gradient - π
8. speed particle/speed wave - 3H/L

9. change of motion with depth - exponential decay

10. good for moderate depths

As this outer harbor buoy will encounter seaway type interactions, a specific wave spectrum must be selected to describe these sea phenomena. The Newmann and Pierce-Moscovitch spectra have particular beneficial application in deep water use (depths over 200 feet), but their applications to shallower waters is generally unreliable. A few coastal water spectra have been developed (24), but have not yet been successfully applied to buoy design considerations. Although a deep water spectrum, the Newmann seaway spectrum has proven considerably effective in buoy design for waters of this moderately shallow depth, and currently is in usage until a better coastal wave spectrum has been experimentally proven for buoy application. This Newmann seaway spectrum may be described as follows:

$$A^2(w) = Cw^{-6} \exp\left(-2g^2/(wV_w)^2\right) \qquad [25]$$

where:

$C = 51.5\ \text{ft}^2/\text{sec}^5$

V_w = wind velocity - ft/sec

w = wave frequency - rad/sec

$g = 32.2\ \text{ft/sec}^2$

$A^2(w)$ = the square of the wave frequency height component

To alter this expression to buoy applications, the following definitions are utilized:

$\theta(w) \equiv$ response amplitude operator of buoy

and

The root mean pitch motion is

$$\theta_\theta = (1/2 \int_0^\infty \theta^2(w)\, A^2(w)\, dw)^{\frac{1}{2}} \qquad [26]$$

The buoy will have a pitch motion equal to the wave slope if encountering very long waves.

Now define

$s(w) \equiv$ maximum slope of unit amplitude wave

Now

$$\lim_{w \to 0} \frac{\theta(w)}{s(w)} = 1 \qquad [27]$$

similarly

$$\lim_{w \to \infty} \frac{\theta(w)}{s(w)} = 0 \qquad [28]$$

Between these above limits, a second order oscillation will correctly simulate buoy action, namely;

$$\frac{\theta(w)}{s(w)} = \frac{1}{[(1-w^2/w_n{}^2)^2 + 4\zeta^2\, w^2/w_n{}^2]^{\frac{1}{2}}} \qquad [29]$$

where:

w_n = buoy natural frequency

ζ = buoy damping ratio

This then approximates a Gaussian distribution of motions as normalized by a least squares fit; such that the buoy

probability of being within the Gaussian is

$$p(w) = f\left(\frac{\alpha-\theta_m}{\theta_\theta}\right) - f\left(\frac{-\alpha-\theta_m}{\theta_\theta}\right) \qquad [30]$$

where:

$f(x)$ = normalized cumulative probability

θ_m = mean pitch angle

α = angle deviation from vertical axis

Studies of spherical buoys under the above Gerstner and Newmann criteria have shown that the three basic motions--pitch, heave, and surge--have a detrimental result on navigational aid effectiveness; and attempts made to limit and reduce their effects, notably their resonances, have been reviewed thoroughly with the following specific application for buoys

1. Pitch motion - a sharply pronounced resonance
2. Heave motion - a slight resonance
3. Surge motion - little or no notable resonance

Obviously the efficient buoy must limit and control all pitch, heave, and surge motions, but the primary concern is the pitch motion resonance, plus previously unmentioned non-linear effects. The use of a current bar or bridle attachment of mooring chain to buoy has proven a great factor in damping <u>all</u> pronounced resonances and motions to acceptable minimums--the bridle attachment is considered the more efficient device and as such, is included in this design (33). For buoys, the above mentioned non-linear instabilities to be considered may be reduced to three problem areas, those being

1. Roll - caused by 180° difference of current and wave effects, although minor problem, no method of total elimination exists; spherical shapes are, however, one of better forms to reduce this inefficiency.
2. Wandering - vortex shedding of unstreamlined form causes hydrodynamic lift; minimized by selection of streamlined spherical body.
3. Heave-roll instabilities - large resonances resulting from heave-roll interactions; unable to completely remove as are a strong function of wave periods; but spherical shape helps reduce degree of resonance motion.

From this review of all buoy motions, it is seen that the mean pitch angle is a critical buoy parameter--a large value for this angle will reduce the overall response of this buoy to all seaway motions; hence a reliable, stable platform. This factor is similarly augmented by tests by Harleman and Shapiro (27), which show that single point moors further abet the mean pitch angle. In other smaller factors, the combined efforts of buoy drag and displacement tend to offset each other in spherical buoy design and as such are neglected; and the spherical shape reduced the response motion to low wave heights through quadratic damping.

Considering all the above factors, the selection of the 8x26 buoy body was considered ideal for this design and purpose, namely;

1. spherical shape - excellent stability characteristics, good backup model testing
2. outer wrapper diameter - 8 feet
3. inner wrapper diameter - 5'8", the structural and damage control member
4. expected lifetime - 20 years
5. chain attachment - for a single point moor use bridle attachment
6. depth of moor - good to 25-250 foot depth
7. mean pitch angle - excellent high value
8. natural period ($1/w_n$) - 5.6 seconds
9. damping ratio (ζ) - 0.08
10. capability - excellent stability and performance characteristics matching navigational aid and isotope power weight criteria
11. availability - currently the standard Coast Guard outer water buoy
12. adaptability - integrates well into this special design

Thus, with the weight limitations of the functional aids and power supply combined with the limited motions stability, the 8x26 spherical form is the best available buoy body structure for this unique design. Numerous buoy body experimental tests for this specific form are included as Figures 15, 16, and 17.

The naval architectural aspects of this specific combination of subsystems is derived and evaluated in the following section.

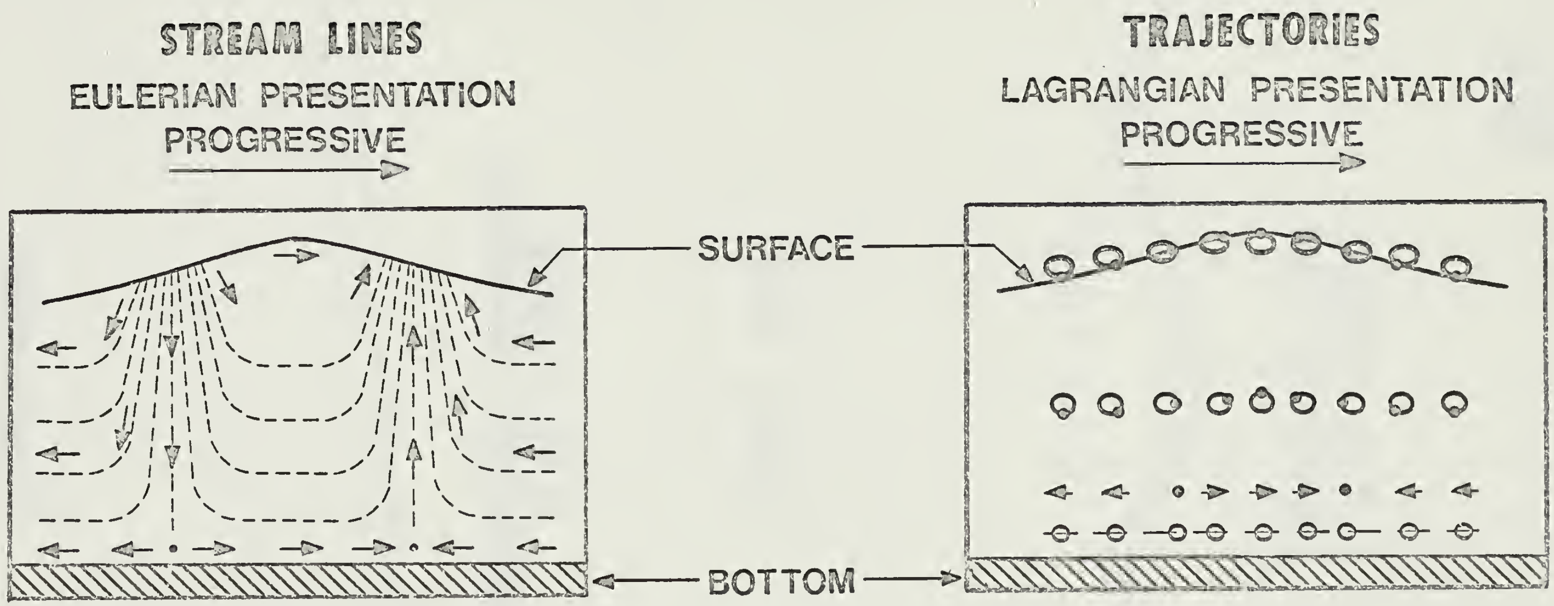

Figure 13 - Ocean Bottom Effects

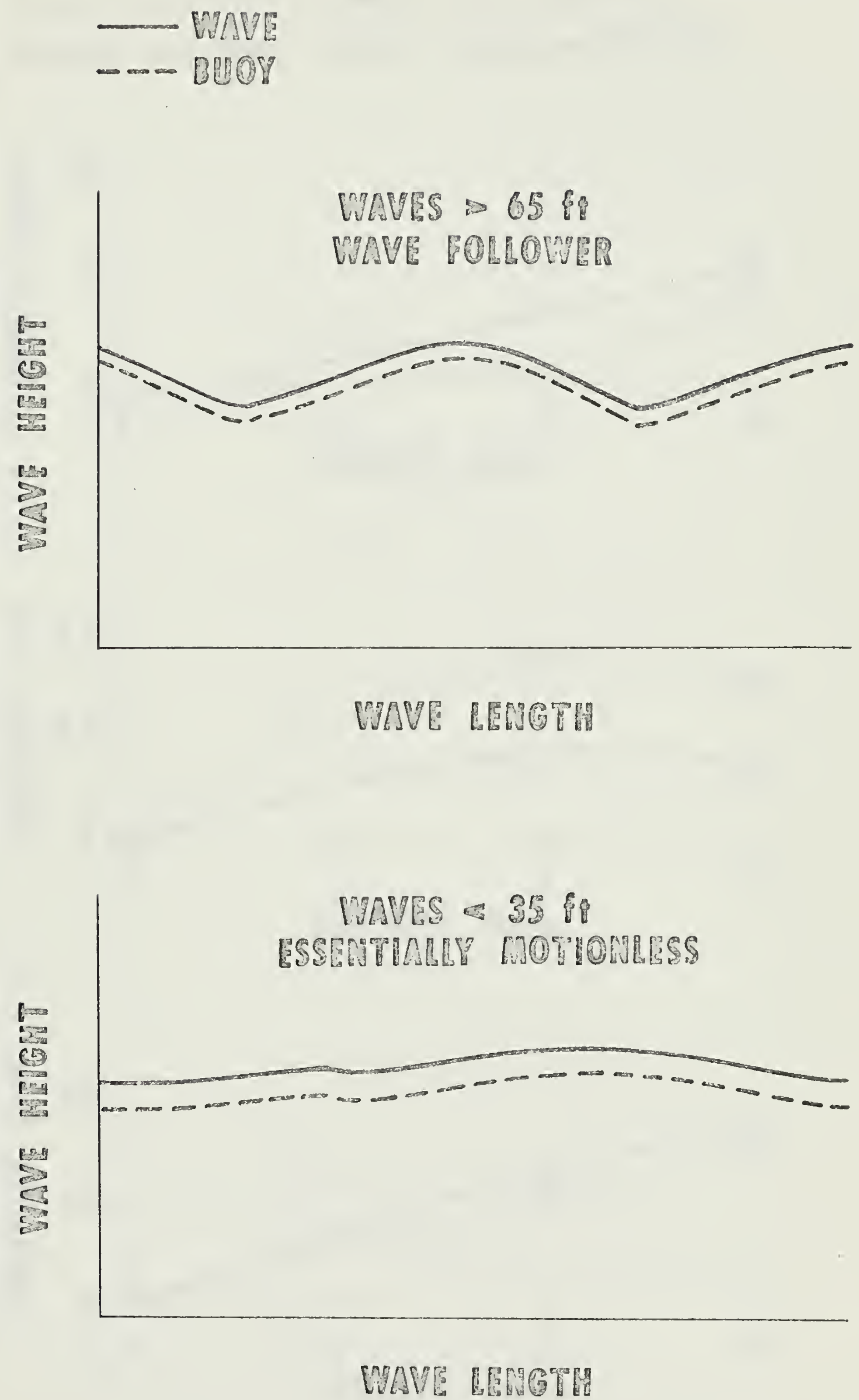

Figure 14 - Buoy Wave Riding Characteristics

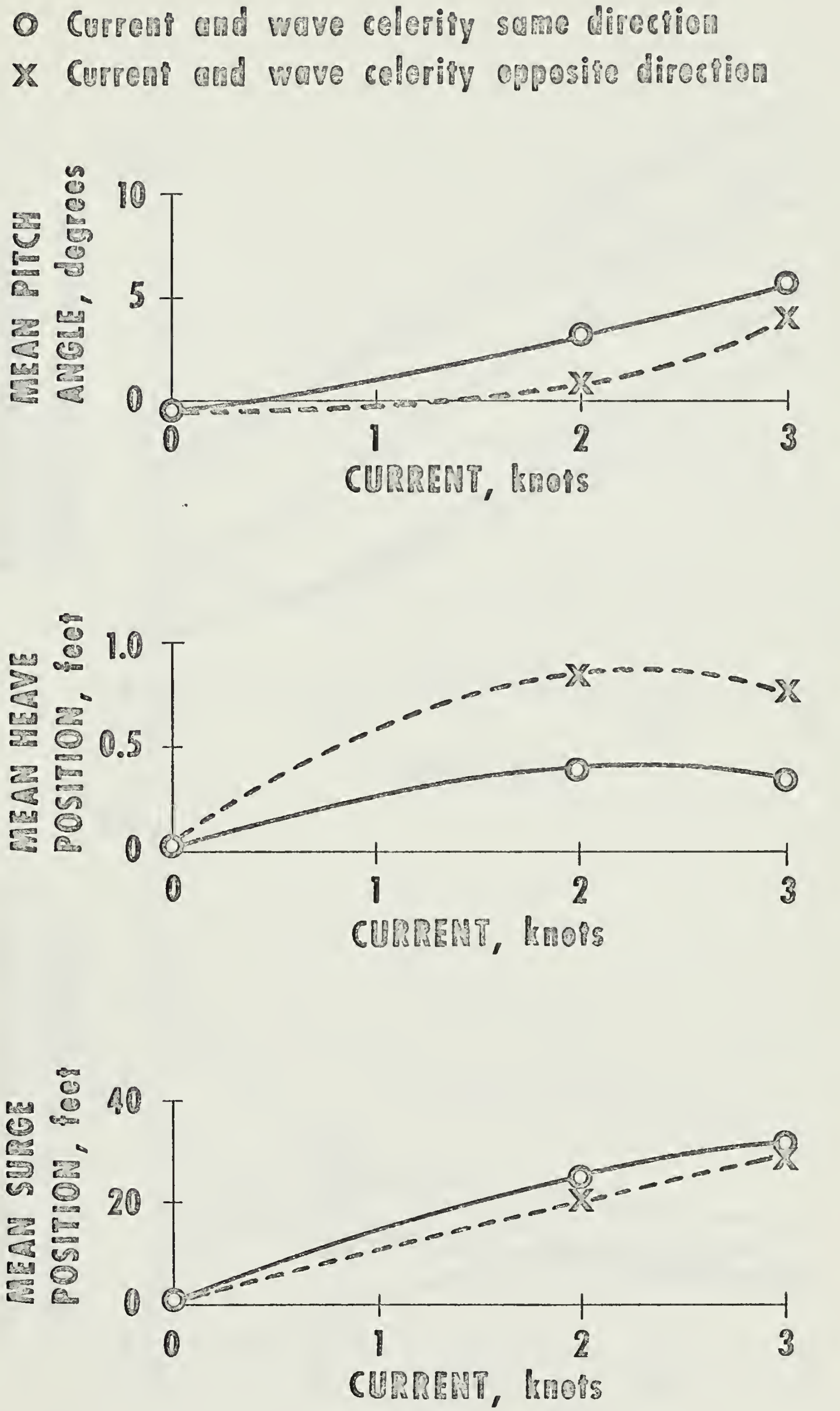

Figure 15 - Heave, Pitch, and Surge Variations with Current

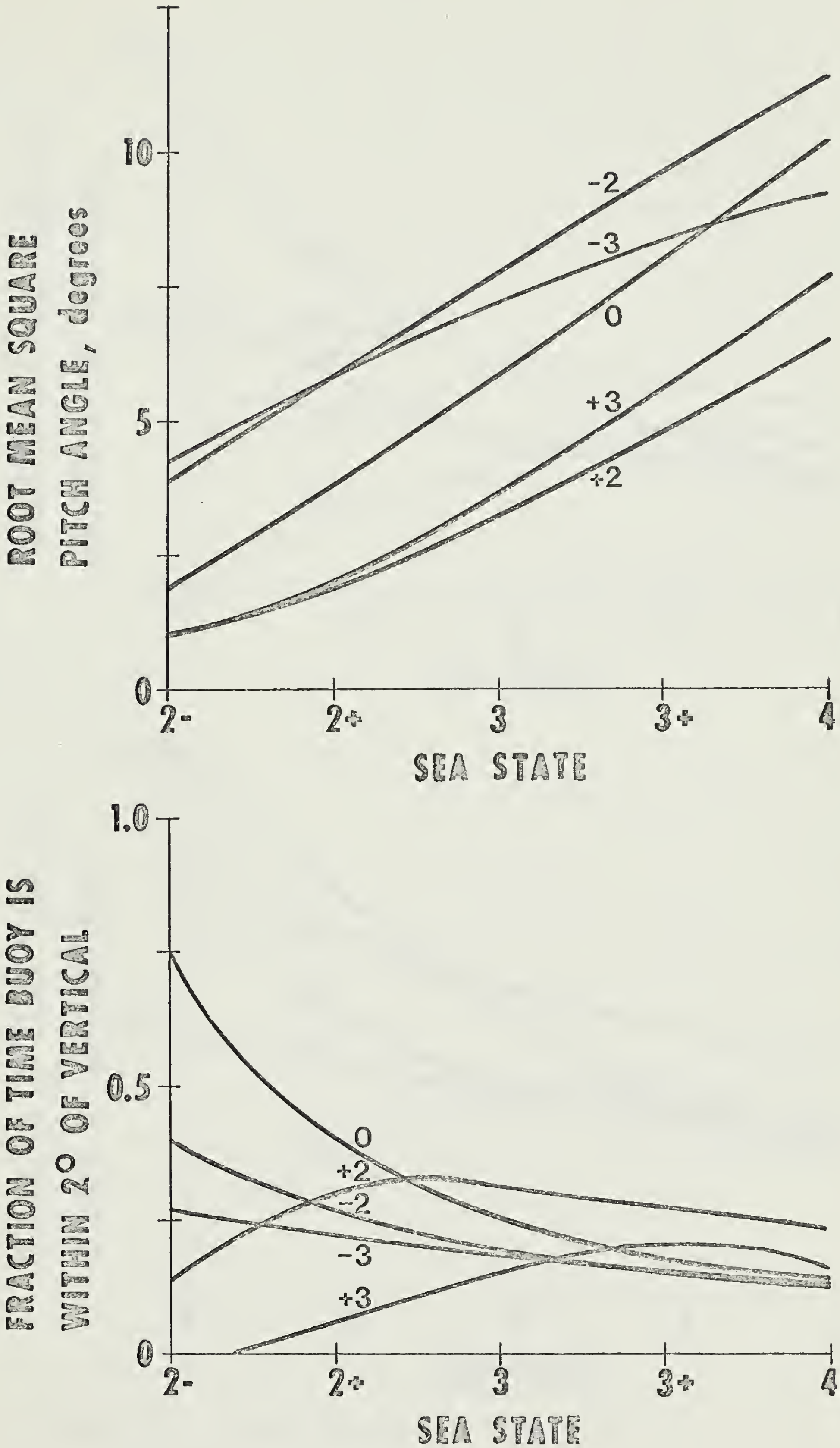

Figure 16 - Buoy-Sea State Motions

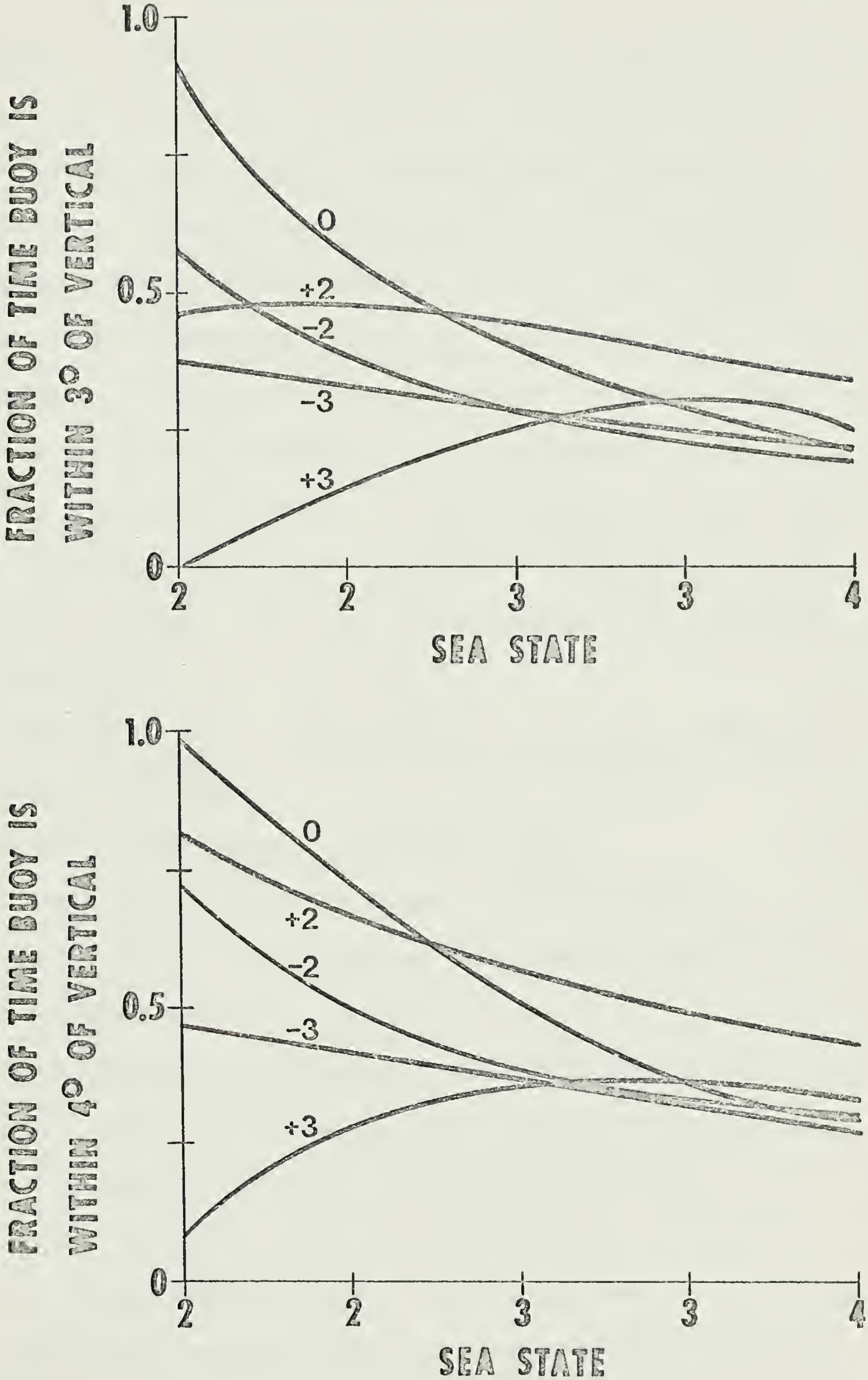

Figure 17 - Buoy-Sea State Interactions

MOORING SYSTEM DESIGN

Although an effective buoy and powering system have been devised, the system must be precisely stationed to realize optimum effectiveness. This is accomplished by means of a mooring system. Actually a mooring system is comprised of three separate constituents, namely; mooring line, sinker weight, and buoy attachment. Each of these components is in itself a separate study, and their combined effectiveness assures buoy location reliability. Unfortunately, a mooring system study must be conducted for each specific locale, as prevailing currents and bottom conditions drastically alter the acceptable system. Thus for this design, the following site was specified:

1. Location - outer Boston Harbor, 12 miles offshore
2. Depth - 70 feet
3. Bottom conditions - extremely rocky
4. Prevailing currents - mixed, light currents

This is in fact a true presentation of the waters and conditions in this one area. (64)

The first design consideration was in proper sizing of the sinker weight. The weight itself may come in various forms, but mainly the anchor and "blob" are used. The "blob" may be either concrete or metal, and is usually just a clump of material in a rectangular shape. The anchor has very attractive holding properties, but the costs of these metallic devices would be uneconomical in any large quantities. Thus the "blob"

or clump has evolved as the primary buoy anchoring device, mainly the concrete sinker as it is extremely cheap (fiscal year 1968 prices: one dollar per hundred pounds). Surprisingly enough, there has been little or no work done to determine the actual minimum weight needed for any given case. The long standing policy is simply if the sinker doesn't hold, use the next heaviest weight. It is known that heavier weights are needed for rocky bottoms, as the holding power there is minimal; while muddy bottoms with their settling and suction action require the least weights (61). But currently, there are no empirical formulae or codes to govern the selection of clump weights, merely the reexamination of past experience on any one specific location. Thus this buoy sinker weight will be governed by local custom, which has been;

> "For a depth of seventy feet with a rocky bottom, the 6,500 lb. concrete clump sinker has proven effective in mooring the standard 8x26 size buoy." (64)

Studies by Drisko (32) have shown that the majority of failures in the buoy system occur in the mooring subsystem, namely in the shackles attaching the mooring line to the buoy. Tension recorders and strain and stress gauges have established the fact that the most likely place for a failure is in this locale as buoy motions yield maximum stress and strain concentrations at that point. Cyclic fatigue and impact loading account for the remaining mooring system failures. Thus for all types of failures, it is desirous to decouple the mooring line from surface excitations. The physical motion of the mooring line may be briefly described as follows:

the bottom of the line moves only slightly, while the upper portions experience continual motion due to current, wave, and wind interactions. Recent testing by the Coast Guard has shown that under the worst storm and sea actions, the tension recorded in the 1.25 inch chain link mooring line of the 8x26 buoy was only 20,000 pounds. This figure appears to be within the recommended safety factor of 5 as proposed by Walton and Polchek (5) in their studies. The ultimate breaking strength of 1.25 inch link chain is 125,000 pounds. This relatively high factor of safety was selected as it experimentally accounts for such loading conditions as fouling, adverse sea conditions, fish bite, vortex shedding, and wave action. As steel fibres have a higher dynamic tension potential than synthetic fibres, they are required for tensile values of this magnitude. The physical size of this mooring line suggests the economical solution of chain link rather than wire rope, as wire rope of this size has a pronounced tendency to coil and kink.

The actual sizing of the mooring line to the buoy is an application of DenHartog's work (11) on a forced vibration problem with linear damping. Harleman (27) has mathematically evolved this solution from the formula

$$m\ddot{x} = -kx + p_o \cos(wt) - c\dot{x} \qquad [31]$$

where:

m = mass

k = spring constant

p_o = magnitude of forcing function

w = frequency of forcing function

c = damping coefficient

x = distance

t = time

to yield the 125,000 pound ultimate breaking strength. It is possible to reach harmonic oscillatory resonances in this line, but studies have revealed this has little effect on line performance.

As this moor would experience the elliptical orbital water motion associated with shallow water moors, this heavier chain would greatly retard the tendency to allow horizontal displacement. However, it is known that taught mooring lines decrease breaking strength by up to 30%, and greatly promote creep failure.

As to the scope of chain to install, this particular aspect of mooring system sizing is again a matter of on-station experience; there are no given formulae or steadfast rules. Here for this location, particular buoy, and bottom, a scope of 3:1 is indicated for this location. Thus a minimum of 210 feet of chain is needed for the seventy foot moor, but as chain only comes in standard shots (90 feet), a total of 270 feet is required.

The mooring system as described thus far must be attached to the buoy, and this is best done by use of a 1.25 inch chain link Y bridle. This Y attached directly to two padeyes on the spherical underwater section of the buoy and the upper chain

end. This bridle is the standard proven coupling device for the 8x26 buoy and its 1.25 inch chain mooring line.

Tests have shown that twisting actions and line kinks can reduce the ultimate strength of moors by up to 20%; thus every effort is made to initially position the buoy correctly. Berteaux (36) has conducted several studies to resolve the variations of tension in mooring lines based on the following empirical expression:

$$T d\phi = (R \sin\phi + F_r(\phi) + W \cos\phi) ds \qquad [32]$$

where:

T = tension

$d\phi$ = change of angle of cable

R = pressure drag

F_r = normal friction drag

ds = element of cable length

W = chain weight per unit length

Where the ϕ is the variance of the cable angle with the vertical at its connection to the buoy; the bottom angle is always assumed to be zero. Experimental results with this expression have been augmented and verified by the practical on-station tension measurements previously noted. Wilson and Garbaccio (4) have conducted similar experimentation into this field in a theoretical vein, but at present no practical findings have confirmed their proposals.

A brief computer study of this particular mooring system is included as Tables XV and XVI.

Thus the mooring system components match the prescribed requirements of this specific buoy location and past experience has shown excellent compatability. A summary of mooring systems characteristics is listed in Table XIV.

TABLE XIV

SUMMARY OF MOORING SYSTEM CHARACTERISTICS

--Sinker--	
Type	Concrete
Dimensions	Rectangular
Weight	6,500 pounds
Availability	One of Coast Guard's standard sinkers
Cost	$1/100 pounds
History	Numerous years of successful application
--Bridle--	
Type	Standard Y fitting
Weight	400 pounds
Classification	1.25 inch steel, link chain bridle
--Mooring Line--	
Type	1.25 inch steel link chain
Scope	3:1
Depth of Moor	70 feet
Length of Chain	270 feet (3 shots)
Safety Factor	5
Ultimate Breaking Strength	125,000 pounds
Maximum Recorded Tension	20,000 pounds
Chain Weight per foot	14.5 pounds/foot

TABLE XV

MOORING LINE COMPUTER STUDY

In order to verify the previously mentioned criteria established for deep water buoys, a computer program was devised to study mooring line tensions and buoy excursions in calm water. This study was based on the catenary equations as applied to underwater chain, namely

$$\text{Tension=TT} = \frac{\text{chain weight per unit foot X scope}}{(\tan(A2)+\tan(A1)) \text{ X } \cos\ (A2)}$$

and

$$\text{Buoy excursion} = X = \text{Horizontal Tension Component X}$$

$$\text{Antilog of } [\tan(\frac{\pi}{4}+\frac{A2}{2})/\tan(\frac{\pi}{4}+\frac{A1}{2})]$$

where:

A2 = angle of chain with the vertical at the buoy

A1 = angle of chain with the horizontal at the bottom

As buoys may have a depth to scope ratio as low as 0.7, the range of 0.7 to 0.95 was studied in 0.05 increments; as were calm water tidal variations of $\pm$ 5 feet in one foot increments from the mean depth of 70 feet.

In the attached computer program and results, it is noted that the tension values were considerably below the 125,000 psi ultimate breaking strength, and buoy excursions were limited well within the maximum dislocation of 100 yards.

For clarity and brevity, the thesis listing of computer output is limited to the mean depth of 70 feet.

```
$JOB              JOB1,KP=29,TIME=2,PAGES=50
      WRITE(6,50)
   50 FORMAT(10X,'MOORING LINE MOTION FOR SPECIAL ISOTOPE BUOY'//
     110X,'STANDARD 1.25 INCH CAST LINK CHAIN IS THE MOORING LINE'//
     210X,'ULTIMATE BREAKING STRENGTH IS 120,000 PSI'//
     310X,'A 6,500 POUND CONCRETE SINKER IS USED'//
     410X,'WITH BOSTON HARBOR LOCALE, ROCKY BOTTOM ENVIRONMENT'//
     510X,'DEPTH OF BOSTON HARBOR MOOR IS 70 FEET'////)
C     VARIABLES ARE.....
C     Y IS THE DEPTH OF WATER
C     S IS THE LENGTH OF SUSPENDED MOORING LINE
C     YS IS THE DEPTH-SCOPE RATIO
C     A1 IS THE ANGLE OF CHAIN WITH BOTTOM
C     A2 IS THE ANGLE OF CHAIN WITH THE VERTICAL
C     A1MAX IS THE MAXIMUM ANGLE OF CATENARY CABLE WHICH IS SUPPORTED
      Y=65.
   33 YS=0.7
      WRITE(6,30)Y
   30 FORMAT(10X,'THE DEPTH OF WATER IS',10X,F6.2,6X,'FEET')
C     WILL STUDY DEPTH-SCOPE RATIOS OF 0.7 TO 1.0
      DO 5 I=1,6
      A1MAX=ARSIN(YS)
      A1MAX=A1MAX*57.29582
      S=Y/YS
      WRITE(6,31)YS,A1MAX,S
   31 FORMAT(/,2X,'YS IS',F6.2,3X,'MAX ANGLE IS',F8.3,5X,'SCOPE',F8.2/)
      WRITE(6,10)
   10 FORMAT(2X,'TT',14X,'H',14X,'X',14X,'XS',14X,'A1',14X,'A2')
   11 A1=0.
C     WILL APPLY STANDARD CATENARY FORMULAE
C     THE VALUES OF A,B,C,DD,E,F,G, AND P ARE DUMMY VARIABLES
      DD=COS(.5*A1)
      E=SIN(.5*A1)
      A2=-2.*(E*DD-YS*DD**2)
    8 F=COS(.5*(A2-A1))
      C=SIN(.5*(A1+A2))
```

Table XV (con't)

```
    1 DIFF=(C/F-YS)/COS(A1)*2.*F**2
      IF(ABS(DIFF/A2)-(.1E-05)) 7,7,2
    2 A2=A2-DIFF
      GO TO 8
    7 G=TAN(A2)
      P=TAN(A1)
    3 H=16.1*S/(G-P)
C     H IS THE HORIZONTAL COMPONENT OF TENSION
      V1=H*P
      V2=H*G
      A=A2/2.
      B=A1/2.
C     X IS THE HORIZONTAL LINE EXCURSION
C     XS IS THE SCOPE-EXCURSION RATIO
      X=H*ALOG((SIN(0.785397+A)/COS(0.785397+A))
     1/(SIN(0.785397+B)/COS(0.785397+B)))*0.1
      XS=X+Y-S
      A3=57.295828*A1
      A4=57.295828*A2
      TT=H/COS(A2)
      WRITE(6,20)TT,H,X,XS,A3,A4
   20 FORMAT(6E15.6)
   43 YS=YS+0.05
    5 CONTINUE
   70 Y=Y+1.
C     FIVE FEET  FROM 70 FEET IN ONE FOOT INCREMENTS
      IF(75.-Y) 40,33,33
   40 WRITE(6,60)
   60 FORMAT(10X,'READ TT AS TENSION VALUES'/
     110X,'READ X VALUES AS HORIZONAL BUOY MOVEMENT'/
     210X,'READ H VALUES AS HORIZONTAL TENSION'/)
      CALL EXIT
      END
$ENTRY
$STOP
```

Table XV (con't)

TABLE XVI

MOORING SYSTEM COMPUTER RESULTS

```
        THE DEPTH OF WATER IS          70.00       FEET

YS IS  0.70   MAX ANGLE IS  44.427     SCOPE  100.00

TT              H               X               XS              A1              A2
 0.171350E 04   0.586500E 03    0.101734E 03    0.717338E 02    0.000000E 00    0.699841E 02

YS IS  0.75   MAX ANGLE IS  48.590     SCOPE   93.33

TT              H               X               XS              A1              A2
 0.156528E 04   0.438279E 03    0.852845E 02    0.619511E 02    0.000000E 00    0.737398E 02

YS IS  0.80   MAX ANGLE IS  53.130     SCOPE   87.50

TT              H               X               XS              A1              A2
 0.144397E 04   0.316969E 03    0.696448E 02    0.521448E 02    0.000000E 00    0.773197E 02

YS IS  0.85   MAX ANGLE IS  58.212     SCOPE   82.35

TT              H               X               XS              A1              A2
 0.134343E 04   0.216431E 03    0.543736E 02    0.420206E 02    0.000000E 00    0.807291E 02

YS IS  0.90   MAX ANGLE IS  64.158     SCOPE   77.78

TT              H               X               XS              A1              A2
 0.125918E 04   0.132179E 03    0.389187E 02    0.311409E 02    0.000000E 00    0.839745E 02

YS IS  0.95   MAX ANGLE IS  71.805     SCOPE   73.68

TT              H               X               XS              A1              A2
 0.118788E 04   0.608779E 02    0.223024E 02    0.186182E 02    0.000000E 00    0.870624E 02
```

BUOY PROTECTION SYSTEMS

As currently constructed, the maximum on-station life of sea water buoys is three years; this limit being established by failure of the mooring system due to a combination of three causes--destructive marine growth, a corrosive salt environment; and sea water electrolysis. Studies by Drisko (32) and Berteaux (36) have shown that the vast majority of failures occur in shackles, namely at the buoy-chain-bridle connections where the constant dynamics of motion (tides, storm, and wave action) accelerates deterioration processes. Review of structural failures reveal severe pitting, stress corrosion, and abrasive action. Unfortunately, nylon and other non-metallic lines do not have the strength necessary for buoys of this size, and the zinc coatings or polyethylene jackets available on small diameter wires are impossible in the construction of the heavy link chain required. As shown in the mooring system section, link chain is the sole material capable of withstanding the loading of the system; however, there is no metallic substance commercially available which can both withstand the deterioration of the environment and be forged into links. As studies (12) have shown, the mooring chain to be more expensive than the buoy itself, it is highly imperative to protect this subsystem adequately. A zinc electrolysis system could be employed, but the constant motion of the buoy causes the links to have only sporadic physical contact; hence the electrical path necessary in electrolysis protection would be erratic, thus the overall

system unreliable. Recent concerted efforts in saltwater protection systems have produced the following solutions which could be easily applied to deep water buoys. First, all underwater sections (chain, buoy bottom, bridle) are coated with a coal tar derivative dip; this has proven extremely effective in detering harmful marine growth, notably barnacles, the prime offender. Muddy bottoms are similiarly associated with hostile anerobic environments. It should be noted that cold tar dips are especially useful in warm water climates, as cold water apparently retards the growth of marine organisms. Similarly anti-corrosive paints have been created for ships which prove equally protective to the exposed buoy structure; hence retarding the corrosive salt action, notably the weakening of rust undercutting. To prevent chafing and minor collision damage from ship-servicing requirements, fender strips of laminated steel and wood are attached to the buoy counterweight tube. Overall electrolysis protection is now a reality through the use of a most novel application. In order to by-pass the intermittant nature of electrical path conduction, a 3/4" galvanized wire is intermingled through the chain, being welded to the concrete weight shackle at the bottom and the bridle at the top. Two 144 pound zincs are attached to the buoy bottom near the bridle to provide the sacrifical metal. For chain of this size, the zinc's sizing is based upon a minimum required 850 millivolt electrolyic potential. The galvanized wire is physically clamped to the chain midsections, and is used solely for a continuous electrical path, although

it could provide some slight degree of reinforcing to the chain maximum tensile loading. Although tests conducted at Wood's Hole Oceanographic Institute (32) are not yet complete, it is assured that the above mentioned protective systems will provide a minimum of seven years on-station time (even after that length of time the zincs still showed no passivation). Although the point will be explored in detail later, early cost estimates show electrolysis protection systems to be actually cheaper than current established periodic maintenance criteria. Encouragingly, these developments have transformed the protection subsystem to one of the most reliable, longest service in the entire system.

The zinc electrolysis protection system is displayed in Figures 18 and 19.

Figure 18 - Electrolytically Protected Buoy Chain

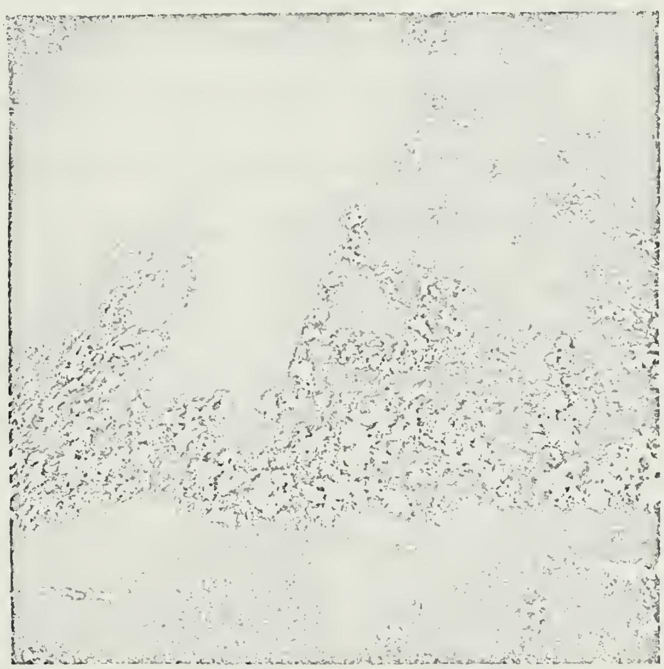

Figure 19 - Zincs Installation on Buoy Body

SHIP SERVICE ASPECTS

With the advent of transistorized navigational aids and concentrated isotopic power generators, there would appear to be no limit to the size and thus capabilities of sea buoys; however, these aids must not only be serviced on station but initially installed, or replaced when inoperable. Currently this formitable task is handled by a small number of 180 foot class buoy tenders. With a crane lifting capability of some twenty tons, these craft can safely, presently handle not only the 9x38 and 8x26, but several larger experimental buoys (10x42). It should be noted that this twenty ton limit includes not only the buoy, but the entire system of concrete sinker, chain, and buoy; and it is a static loading, hence the ability to work in rough seas is severely limited. The three phases of the buoy tender's scenario--installation, on-station servicing, and removal will now be reviewed.

The installation of buoys is a relatively difficult task, as the buoy must not only be precisely navigationally located, but safely positioned. Once on station, the buoy would be checked for potential radiation hazards by an E-500B beta survey meter, electronic aids checked, and then launched in the following manner. The buoy is first placed over the side and held near the vessel; the concrete weight and chain are then released, this procedure involving three phases--free fall, pendulum mode, and relaxation. The chain tension will reach a maximum just before bottoming, and will vary according

to

$$T_{une} = T_{initial} + (W-B) \cos \alpha \qquad [33]$$

where:

T = tension

W = weight of anchor and concrete sinker in pounds

B = buoyancy of line in pounds

α = angle chain makes with vertical

Naturally turns and kinks in the line are to be avoided as kinks may reduce the strength of the moor by up to twenty percent (4). Once positioned, the buoy is then navigationally rechecked for proper functioning of all aids and correct location. Coast Guard Regulations allow only a maximum one hundred yard error in locating outer sea buoys, as a one degree lateral error will produce a one-sixth mile error at a six mile siting.

The on-station servicing of buoys unfortunately is concerned mainly with repair of malfunctions. Current practices require the mooring line to be pulled up and checked every eighteen months, batteries renewed every two years, and flasher light bulb assemblies replaced every 650 days. Nickel-cadmium batteries have extended useful battery life to over five years and although experimental results are encouraging, the 650 day lifetime appears to be the current limit in flasher light lifetime. The cathodic protection system will reduce mooring line failures, but buoy tenders do carry spare chain in standard ninety foot sections (shots), which can be installed on-station.

As the isotopic power generator is located in the counterweight portion below the water, periodic radiation surveys would be futile. As all electronic components have greater than five year life expectancies, it appears the tenders will need make only infrequent visits to replace flasher light bulb assemblies--a dramatic improvement over existing servicing.

The removal of buoys is merely a reversal of the installation procedures; the chain and anchor are taken aboard first, then the buoy. Here, an immediate beta survey would be necessary to ascertain radiological safety for the crew members.

To accommodate large work schedules, the deck arrangement of the existing tenders is ideally constructed to allow safe storage and transit of up to three special isotope buoys. Naturally it is economically unfeasible to design a new class of buoy tenders to handle this unique buoy design. By maximizing buoy functions and closely adhering to weight tolerances, the buoy as designed will integrate well into existing 180 foot class buoy tenders and their functional abilities.

See Table XVII for a complete description of buoy tending characteristics.

TABLE XVII

SUMMARY OF BUOY TENDER CHARACTERISTICS

Type	Hornbeam-WLB class
Length	180 feet
Beam	37 feet
Mean draft	12' 5"
Displacement	935 tons
Speed	13-14 knots
Age	28 years
Cruise	12-13 knots
Carry load	3 large sea buoys
Boom capacity	20 tons
Boom safety factor	1.5
Cruise range	7000 miles @ 12 knots
Total annual operating costs	$284,400
Replace buoys	five year interval
Inspect buoys	650 day intervals
Buoytending fuel costs	$19.30 per hour

NAVAL ARCHITECTURE PARAMETERS

To borrow from an old naval architecture axiom--"a ship (buoy) must float, and float upright". This statement is especially true of a buoy where stability is a must for efficient buoy functioning. The critical parameters calculated in the appended computer program are: buoy weight, total displacement, center of gravity, center of buoyancy, metacentric height, radius of gyration, righting moments, center of wind pressure, time period, freeboard, total weight for a buoy tender crane to handle, and a sample heel calculation. As noted in the computer output, the final stability results are excellent; all buoy parameters satisfy all established limits. In fact the results far surpass the author's original estimates. The computer program and results are included as Tables XVIII and XIX.

It should be noted that this program as designed could study the naval architecture parameters of any potential buoy design.

TABLE XVIII

NAVAL ARCHITECTURE PARAMETERS COMPUTER STUDY

In order to reduce the laborious, lengthy longhand work involved with buoy stability calculations, it is advantageous to devise a simple computer program to accomplish this goal. All weights and corresponding lever arms for each component buoy part were taken from existing Coast Guard listings (13).

Using these weights and lever arms, the various moments were established about the base line, and the center of gravity and center of buoyancy located. Similarly the displacement, water plane height, metacentric height, and freeboard were established. With a moment of inertia calculation, the radius of gyration, period of oscillation, and heel angle were then determined. Briefly the formulae utilized in order of presentation are

$$\text{center of gravity} = CG = \frac{\text{summations of moments}}{\text{total buoy weight}}$$

$$\text{displacement} = DISPL = \frac{\text{total buoy weight}}{\text{salt water density}}$$

$$\text{center of buoyancy} = CB = \frac{\text{summation of displacement moments}}{\text{total displacement}}$$

$$\text{period of oscillation} = TIMPER = 2\,\pi\sqrt{\frac{k^2}{GM \cdot g}}$$

$$\text{buoy heel} = OB = \frac{2 \cdot TT \cdot WP}{WP^2 - TIMPER^2}$$

where:

TT = wave height

WP = wave period

$g = 32.2$ ft/sec^2

GM = metacentric height

k^2 = radius of gyration = $\frac{\text{moment of inertia}}{\text{total weight}}$

A review of the computer results shown all buoy stability characteristics are well above minimum criteria, and as such, this special design should encounter no stability problems within the proposed five year on-station lifetime.

```
$JOB            JOB1,KP=29,TIME=3,PAGES=50
      DIMENSION A(60),B(60),G(8),D(60),W(8),C(60),PTMO(60)
      DIMENSION AA(6),BB(6),VER(55),X(3),Y(5),V(5),GC(8),PM(8)
      WRITE(6,10)
   10 FORMAT(10X,'NAVAL ARCHITECTURE PARAMETERS'/)
      READ(5,20) N, (A(I),B(I),C(I), I=1,N)
   20 FORMAT(I2/(6F10.2))
      READ(5,44) M, (G(K), K=1,M)
   44 FORMAT(I2/(4F10.2))
      DO 1  I=1,60
      D(I)=A(I)*B(I)
    1 CONTINUE
      DO 2  J=1,60
      PTMO(J)=D(J)*C(J)
    2 CONTINUE
      F=0.
      DO 3  K=1,60
      F=F+D(K)
    3 CONTINUE
      DO 4   J=1,8
      W(J)=0.
      PM(J)=0.
    4 CONTINUE
      WRITE(6,11)  F
   11 FORMAT (10X,'TOTAL WEIGHT IS',3X,F10.1,3X,'POUNDS'/)
      W(1)=D(1)
      PM(1)=D(1)*C(1)
      DO 5  M=2,21
      W(2)=W(2)+D(M)
      PM(2)=PM(2)+D(M)*C(M)
    5 CONTINUE
      ZZ=F
      DO 6  N=22,29
      W(3)=W(3)+D(N)
      PM(3)=PM(3)+D(N)*C(N)
    6 CONTINUE
```

Table XVIII (con't)

```
      DO 7   I=30,34
      W(4)=W(4)+D(I)
      PM(4)=PM(4)+D(I)*C(I)
    7 CONTINUE
      DO 8   J=35,47
      W(5)=W(5)+D(J)
      PM(5)=PM(5)+D(J)*C(J)
    8 CONTINUE
      DO 9   K=48,52
      W(6)=W(6)+D(K)
      PM(6)=PM(6)+D(K)*C(K)
    9 CONTINUE
      DO 50   L=53,55
      W(7)=W(7)+D(L)
      PM(7)=PM(7)+D(L)*C(L)
   50 CONTINUE
      DO 51   M=56,60
      W(8)=W(8)+D(M)
      PM(8)=PM(8)+D(M)*C(M)
   51 CONTINUE
      DO 52   N=1,8
      GC(N)=PM(N)/W(N)
   52 CONTINUE
      WRITE(6,12)
   12 FORMAT (10X,'THE TOTAL MOMENT DIVIDED BY THE TOTAL'/
     110X,'WEIGHT EQUALS THE CENTER OF GRAVITY'/)
      SM=0.
      DO 53   J=1,8
      SM=SM+W(J)*G(J)
   53 CONTINUE
      CG=SM/F
      WRITE(6,13) CG
   13 FORMAT(10X,'CG IS',3X,F10.2,3X,'FEET ABOVE BASE LINE AXIS'/)
      DENSAL=64.0
      DISPL=F/DENSAL
      WRITE(6,15) DISPL
```

Table XVIII (con't)

```
15 FORMAT(10X,'DISPLACEMENT IN SALT WATER IS'/
  110X,'WEIGHT DIVIDED BY DENSITY'/
  210X,'SALT WATER DISPLACEMENT IS',3X,F10.2,3X,'CUBIC FEET'/)
   FH=15.9
   READ(5,22) N,(V(I),Y(I), I=1,N)
22 FORMAT(I2,10F6.2)
   DX=0.
   DO 54 J=1,5
   DX=DX+V(J)
54 CONTINUE
   WM=0.
   DO 55 K=1,5
   WM=WM+Y(K)*V(K)
55 CONTINUE
   WRITE(6,16)
16 FORMAT(10X,'THE TOTAL MOMENTS DIVIDED BY THE TOTAL'/
  110X,'DISPLACEMENTS IS THE CENTER OF BUOYANCY'/)
   CB=WM/DX
   WRITE(6,17) CB
17 FORMAT(10X,'CB IS',3X,F10.2,3X,'FEET ABOVE BASE LINE'/)
   R=4.0
   XAREA=3.14159*R**2
   DCYL=V(5)/XAREA
   READ(5,23) N,(X(I), I=1,N)
23 FORMAT(I2,3F5.2)
   WPHT=DCYL
   DO 56  M=1,3
   WPHT=WPHT+X(M)
56 CONTINUE
   WRITE(6,18) WPHT
18 FORMAT(10X,'THE WATER PLANE IS A PLANE THROUGH'/
  110X,'THE BUOY AT THE WATER LINE'/
  210X,'THE WATER PLANE IS',F10.2,3X,'FEET ABOVE BASE'/)
   WRITE(6,80) FH
80 FORMAT(10X,'THE WATER PLANE CALCULATED WITHOUT TAKING'/
  110X,'INTO CONSIDERATION THE DOWNWARD PULL ON '/
```

Table XVIII (con't)

```
  210X,'MOORINGS BY CURRENT, WIND, OR WAVE ACTION'/
  310X,'FOCAL HEIGHT IS',F10.2,3X,'FEET ABOVE SURFACE'/)
   SHHT=15.10
   FRBD=SHHT-WRHT
   FLIP=3.14159*(2.*R)**4/64.0
   BM=FLIP/DX
   GM=BM+CB-CG
   WRITE(6,82) FRBD,FLIP,GM
82 FORMAT (10X,'FREEBOARD IS',F10.2,3X,'FEET'/
  110X,'THE METACENTER IS A MEASURE OF STABILITY'/
  210X,'MOMENT OF INERTIA IS',3X,F9.4,3X,'FEET FOURTH'/
  310X,'METACENTRIC HEIGHT IS',F10.2,3X,'FEET'/)
   READ(5,24) N,(AA(I),BB(I), I=1,N)
24 FORMAT(I2,12F6.1)
   TA=0.
   DO 57  J=1,6
   TA=TA+AA(J)
57 CONTINUE
   TM=0.
   DO 58 K=1,6
   TM=TM+AA(K)*BB(K)
58 CONTINUE
   CWP=TM/TA
   CC=0.11320
   RM=GM*CC*F
   WX=RM/(CWP*TA)
   WRITE(6,84) CWP,RM,WX
84 FORMAT(10X,'CENTER OF WIND PRESSURE IS',F10.2,3X,/
  110X,'FEET ABOVE MOORING POINT'/
  210X,'RIGHTING MOMENT IS',2X,F10.3,3X,'FOOT-POUNDS'/
  310X,'PRESSURE IS',2X,F6.2,3X,'POUNDS/SQ.FOOT'/
  410X,'THUS WIND VELOCITIES EXCEEDING 42 MILES/HOUR'/
  510X,'WILL INCLINE BUOY TO EXTENT THE LIGHT '/
  610X,'WILL NOT BE VISIBLE'/)
   DO 59  J=1,55
   VER(J)=ABS(CG-B(J))**2
```

Table XVIII (con't)

```
59 CONTINUE
   BORE=0.
   DO 60 K=1,55
   BORE=BORE+VER(K)*A(K)
60 CONTINUE
   DO 61 L=56,60
   F=F-B(L)
61 CONTINUE
   GYRATE=BORE/F
   TIMPER=2.*3.14159*(GYRATE/(GM*32.2))**0.5
   WRITE(6,86) GYRATE,TIMPER
86 FORMAT(10X,'RADIUS OF GYRATION IS'F10.2/
  110X,'TIME PERIOD IS',F10.2,3X,'SECONDS'/
  210X,'PERIOD DEFINED AS ENTIRE OSCILLATION FROM SIDE  TO SIDE'/
  310X,'WILL ASSUME A 260 FOOT WAVE, WITH'/
  410X,'A 17 FOOT HEIGHT, A 7 SECOND PERIOD'/
  510X,'TO STUDY HEEL ACTION'/)
   TT=7.5
   ANCH=6500.0
   CHAIN=2600.0
   WP=7.0
   OB=TT*WP**2/((WP**2)-(TIMPER**2))
   TOTWGT=77+ANCH+CHAIN
   WRITE(6,87)OB,CG,CB,GM
87 FORMAT(10X,'BUOY HEEL ANGLE IS',F10.2,3X,'DEGREES'/
  110X,' WORK DERIVED FROM E.L. ATTWOOD AND H.S. '/
  210X,'PENGELLYS -THEORETICAL NAVAL ARCHITECTURE -1939'//
  350X,'SUMMARY'////
  410X,'CG IS',F10.2,3X,'FEET'/
  510X,'CB IS',F10.2,3X,'FEET'/
  610X,'GM IS',F10.2,3X,'FEET'/)
   WRITE(6,88) DISPL,TIMPER,TOTWGT
88 FORMAT(10X,'DISPLACEMENT IS',F10.2,3X,'FEET CUBED'/
  110X,'TIME PERIOD IS',F10.2,3X,'SECONDS'/
  210X,'THE TOTAL WEIGHT TO BE HANDLED BY THE'/
  310X,'BUOY TENDER CRANE IS',F10.2,3X,'POUNDS'//)
```

Table XVIII (con't)

```
      CALL EXIT
      END
$ENTRY
60
     112.00       1.00         .87         .75       16.00         .60
        .20      60.00        5.00         .75        3.00        2.30
       1.70       6.00        5.40      225.00        1.00        3.50
      75.00       3.00        3.50        1.25        3.00        4.00
      20.00       3.00        5.50      350.00        1.00        9.50
      71.00       1.00       11.20       10.40        6.00       10.30
       6.50       3.00       11.10       17.00        1.00       11.10
       5.00       3.00       11.00       15.00        1.00        6.00
      54.00       3.00        5.80       10.70        6.00        4.60
      23.00       3.00         .50       10.00        1.00       20.00
       6.00       1.00       21.00      112.00        2.00        7.36
       3.00       2.00        7.25      123.00        2.00        7.20
       1.00      24.00        7.25       11.00        4.00        6.34
     464.00       2.00        3.60       32.00        2.00         .05
      20.00       2.00         .23       28.30       12.00        2.70
      35.00       1.00        4.20       75.00        1.00        4.10
      20.00       1.00        4.50        5.00        2.00        3.20
     811.00       1.00        6.83      811.00        1.00         .34
    1849.00       1.00        3.58      150.00        1.00        4.50
     150.00       1.00        2.58       15.00        4.00        6.70
      15.00       2.00         .58       83.00        2.00         .58
      46.00       3.00        6.75       46.00        1.00         .58
      80.00       2.00         .60       60.00        1.00        6.80
     280.00       1.00         .10       16.00        6.00        8.25
      16.00       2.00        4.62        1.00        4.00        4.62
      38.00       1.00        4.62      730.00        1.00        4.27
      75.00       1.00        2.10        6.00        1.00        2.10
    3993.10       1.00        1.20      227.00        1.00         .00
      27.00       5.00         .00       51.00        1.00         .00
     998.00       1.00         .00     -197.00        1.00         .00
 8
      26.00      20.96       13.67       12.04
```

Table XVIII (con't)

```
    12.04       4.74        .87       8.67
 5  7.96   .87  1.68  4.74   .80  4.62 22.25  8.96206.94 11.29
 3  .70 6.69 2.10
 6 40.00  6.10   2.10 17.33 17.20 12.82  4.20  7.21  3.8  6.75 13.00  5.70
$STOP
```

Table XVIII (con't)

TABLE XIX

NAVAL ARCHITECTURE PARAMETER COMPUTER RESULTS

```
NAVAL ARCHITECTURE PARAMETERS

TOTAL WEIGHT IS       14468.0   POUNDS

THE TOTAL MOMENT DIVIDED BY THE TOTAL
WEIGHT EQUALS THE CENTER OF GRAVITY

CG IS           9.32   FEET ABOVE BASE LINE AXIS

DISPLACEMENT IN SALT WATER IS
WEIGHT DIVIDED BY DENSITY
SALT WATER DISPLACEMENT IS       226.06   CUBIC FEET

THE TOTAL MOMENTS DIVIDED BY THE TOTAL
DISPLACEMENTS IS THE CENTER OF BUOYANCY

CB IS          10.66   FEET ABOVE BASE LINE

THE WATER PLANE IS A PLANE THROUGH
THE BUOY AT THE WATER LINE
THE WATER PLANE IS      13.61   FEET ABOVE BASE

THE WATER PLANE CALCULATED WITHOUT TAKING
INTO CONSIDERATION THE DOWNWARD PULL ON
MOORINGS BY CURRENT, WIND, OR WAVE ACTION
FOCAL HEIGHT IS      15.90   FEET ABOVE SURFACE

FREEBOARD IS       1.49   FEET
THE METACENTER IS A MEASURE OF STABILITY
MOMENT OF INERTIA IS    201.0618   FEET FOURTH
METACENTRIC HEIGHT IS      2.18   FEET

CENTER OF WIND PRESSURE IS      9.90
FEET ABOVE MOORING POINT
RIGHTING MOMENT IS    3565.800   FOOT-POUNDS
PRESSURE IS    0.06   POUNDS/SQ.FOOT
THUS WIND VELOCITIES EXCEEDING 42 MILES/HOUR
WILL INCLINE BUOY TO EXTENT THE LIGHT
WILL NOT BE VISIBLE

RADIUS OF GYRATION IS     51.85
TIME PERIOD IS       5.40   SECONDS
PERIOD DEFINED AS ENTIRE OSCILLATION FROM SIDE  TO SIDE
WILL ASSUME A 260 FOOT WAVE, WITH
A 17 FOOT HEIGHT, A 7 SECOND PERIOD
TO STUDY HEEL ACTION

BUOY HEEL ANGLE IS     18.56   DEGREES
 WORK DERIVED FROM E.L. ATTWOOD AND H.S.
PENGELLYS -THEORETICAL NAVAL ARCHITECTURE -1939

                                        SUMMARY
```

TABLE XIX (con't)

```
CG IS       9.32   FEET
CB IS      10.66   FEET
GM IS       2.18   FEET

DISPLACEMENT IS    226.06   FEET CUBED
TIME PERIOD IS       5.40   SECONDS
THE TCTAL WEIGHT TO BE HANDLED BY THE
BUOY TENDER CRANE IS  23568.00   POUNDS
```

COST EFFECTIVENESS

Perhaps the major disadvantage of installation of nuclear powered buoy systems is the relatively expensive cost of the isotope itself; however, it must be remembered that isotope costs are cyclic prices in that increased demand drastically reduces costs. This cost effectiveness study is based upon current available costs of all materials, and is based on a one buoy purchase. It is also assumed that for study purposes that the buoys in consideration will each have the identical optimum navigational aid payload as described in this thesis.

First it is advantageous to review the users of this outer harbor buoy network, and these are: commercial, recreational, fishermen, and governmental shipping. Surveys by Geonautics (35) have further defined this listing to be the following percentages of the total shipping fleet

1. Commercial - 61%
2. Fishermen - 64%
3. Recreational -54%
4. Governmental - (classified)

Naturally these percentages would vary for inner harbor usage.

Further studies to indicate future shipping trends and patterns by these four interests have projected the following expected increased in deep water buoy usage by 1983. (37)

1. Commercial - up 100 %
2. Fishing - up 55%
3. Recreational - up 300%

4. Governmental - up at least 100% but still classified

This places a considerable strain on existing buoy facilities and capabilities and calls on increased reliability and efficiency within the next decade--an increase which could hopefully be met by isotope powered buoys. In 1966 alone, some 413 billion dollars or 0.6% of the Gross National Product was involved in maritime shipping, all of which is guided by the Coast Guard lateral buoy system.

To further realize the economical impact of this buoy system, the port of Boston is analyzed for the calendar year 1966 for total shipping and cash losses due to delay in shipping because of weather conditions detering existing aids to navigation utilization. This data is presented in Table XX.

In addition to the above mentioned losses, navigational errors and accidents accounted for 42.7 million dollars in losses in 1967 alone.

To anticipate user demands, a thorough study was initiated in 1968 to ascertain all the features in an optimum buoy system; with the following results

1. user costs - $100-$500
2. power - 12 volt
3. user training time - 12 hour maximum
4. availability - 24 hour continuous
5. resolution time - 0.5 to 3 minutes
6. range - to 50 miles

Thus contemporary buoy systems would need to be substantially improved to meet these specifications.

Now it is advantageous to compare the two competitive navigational buoys; one the standard 8x26 acetylene buoy now in service; and second, the proposed isotope powered replacement.

This phase of study would obviously revolve about the acquisition costs. As the standard buoy has only a three year on-station lifetime, the costs have been ratioed up to five years in order to have a meaningful comparison. These results are presented as Table XXI.

As can readily be seen, the present cost projection figures strongly favor the standard 8x26 buoy; however, such factors as the reliability, dependability, and engineering superiority of the isotope system cannot receive a dollars and cents value, and this aspect cannot be emphasized too strongly. As mentioned earlier however, the repeated demand for radioisotopes can and will definitely lower the consumer price; and as Strontium-90 is obtained from reactor wastes, that stockpile should be radically increasing with more nuclear power stations coming into realization.

Prototype stations such as the SNAP series have proven experimentally beneficial, however, their costs were also prohibitive. In fact, the SNAP 7D buoy of comparable size and powering costs over $200,000 dollars and this was constructed in 1964; thus fuel costs have obviously dropped by a factor of roughly two already. As the isotope buoy is deemed superior engineering-wise, projected costs would make it economically feasible by about 1976, providing current costs can be extrapolated.

A thorough review of all results will be made in the conclusions section.

TABLE XX

SHIPPING COSTS SURVEY

Boston Harbor, 1966

Type Vessel	Number Entering Port	Losses in Dollars Through Lost Navigational Time
Tow boats	2,977	$ 1,252,210
Dry Barges	403	$ 6,083
Tanker Barges	2,618	$ 65,070
Passenger, Cargo Vessels--American and Foreign	4,713	$11,304,739
Fishing Craft	27,048	$ 4,362,936
Totals	37,759	$16,991,038.00

Based on standard delay in port time of $170/hr/vessel miscellaneous costs.

TABLE XXI

BUOY COST COMPARISON (5 year comparison)

(based on fiscal year 1967 costs)

Component	Standard Buoy	Isotope Buoy
Lifetime	3 years	5 years
Navigational aids	$ 347.50	$ 347.50
Batteries	$ 1,516.00	$ 436.00
Buoy tender fuel differential costs	$ 520.00	$0
Buoy body and appendages	$ 3,454.00	$ 3,454.00
Parts replacement	$ 276.40	$ 276.40
Acetylene fuel	$ 2,625.00	$0
Strontium-90 generator	$0	$94,277.56
Chain and anchor	$ 1,101.00	$ 1,101.00
Overhaul*	$18,000.00	$0
Cathodic protection system (current practice)	$0	$ 360.00
Totals	$27,839.90	$100,252.46

*Note: The overhaul costs are based on the following breakdown:

1. Removal and installation - 63%
2. Overhaul ground tackle - 23.8%
3. Overhaul buoy body - 13.2%

CONCLUSIONS

The earlier qualified success of the experimental SNAP 7D buoy design fostered this thesis concept of a practical design for an isotope powered replacement for the Coast Guard's existing outer harbor, deep water buoys. Limitations in power and servicing requirements had restricted the use of new electronic navigational aids to land establishments and other testing with plastics had merely stirred the relatively stagnant field of buoy development. The notion of a compact, dependable, long service isotope fuel system powering an optimum navigational aids package while realizing current advances in mooring protection systems, and buoy design was not so much to combine these engineering advances in thesis form; but to promote this idea as the way to solve both the future buoy needs of the Coast Guard and the isotope market of the Atomic Energy Commission.

Each subsystem was carefully devised not only to maximize its particular effectiveness, but to blend efficiency into the whole of the buoy design. Basic concepts concerning the engineering feasibility of this design were strongly affirmed by the three computer programs devised; not only does this buoy meet all the minimum specifications for engineering practicality, but the system proves to be immensely superior to the standard 8x26 buoy in all aspects except price, and as noted this last barrier should be surpassed in 1976 if current price trends can be accurately extrapolated. The 8x26 buoy provided the

parent for this design because it is the present standard deep water buoy; later it subsequently provided an excellent comparison for the completed isotope design.

Beyond future possible system development with plastic buoys or more efficient thermoelectric conversion devices, the summarized results of this design, presented as Table XXII, speaks for itself; this buoy design surpasses all existing buoys in combining the functions of a buoy with a dependable power system for a long on-station service time.

Naturally model tests would be necessary to establish isotope safety aspects for Atomic Energy Commission licensing requirements, and towing tank tests to verify buoy performance. It is believed, however, that these tests would definitely affirm the soundness of this proposed engineering design.

A sketch of the final buoy design is included as Figure 20.

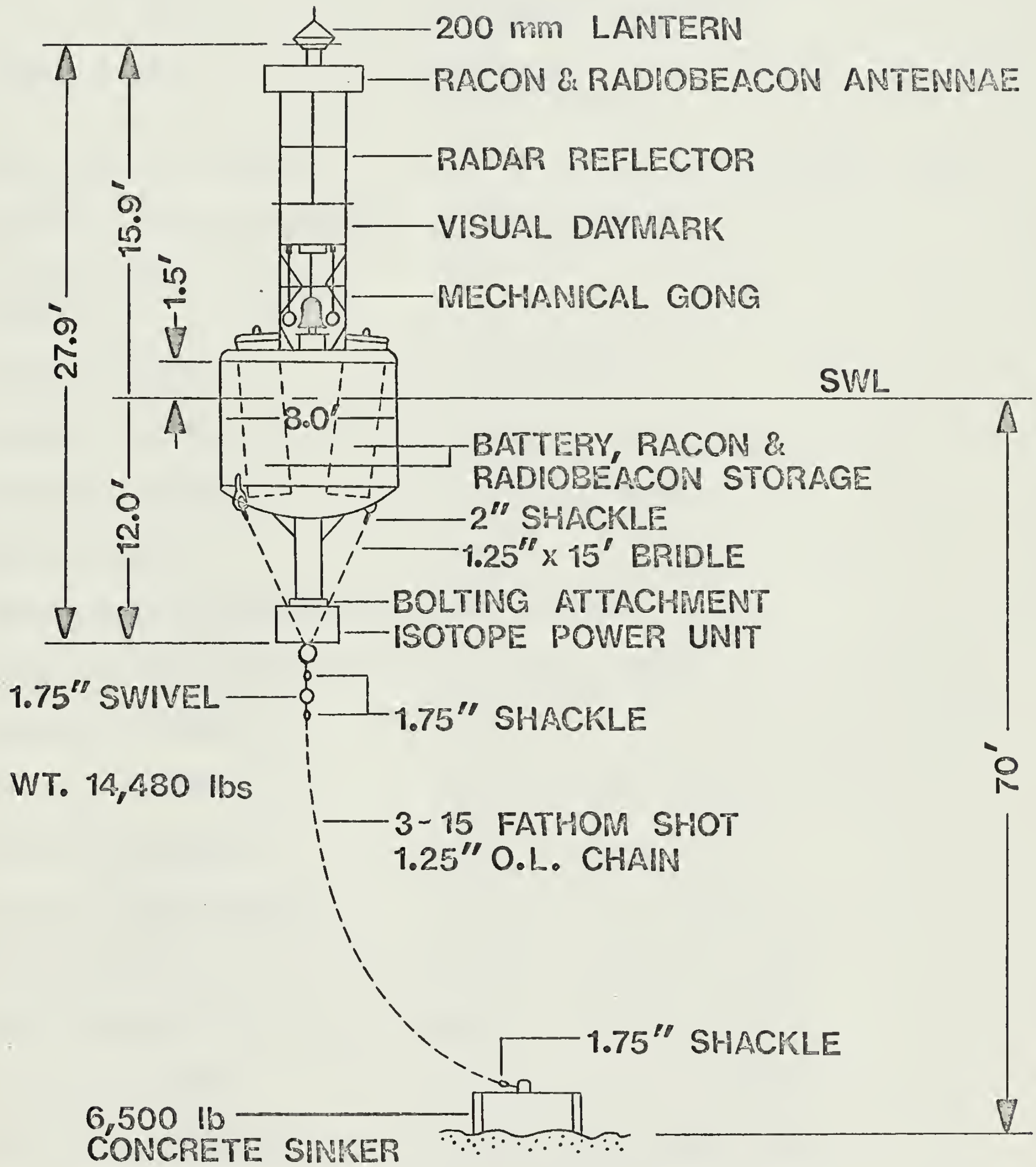

Figure 20 - Finalized Buoy Sketch

TABLE XXII

FINAL DESIGN SUMMARY

1.	On-station lifetime	5 years	
2.	Buoy location	Outer Boston Harbor 12 miles offshore	
3.	Depth of moor	70 feet Rocky bottom	
4.	Buoy tending vessel	180 ft class Coast Guard Tender	
5.	Maximum lifting capacity	40,000 pounds	
6.	Maximum number buoys carried	3	
7.	Height of Buoy	27.9 feet	
8.	Diameter of Buoy	8 feet	
9.	Weight of Buoy	14,480.0 pounds	
10.	Buoy material	Steel	
11.	Total power requirement	56.0 watts	
12.	Navigational Aids, Ranges and Power Useage		
	Mechanical Gong	0.3	0
	Radar Reflector	7.5	0
	Sonar Reflector	3.0	0
	Visual Daymarkings	4.4	0
	Radar Beacon	9.0	1.0
	Radio Beacon	20.0	25.0
	Flashing Light	4.6	30.0
13.	Center of buoyancy	10.66 feet above base	
14.	Center of gravity	9.32 feet above base	
15.	Radius of gyration	51.85	

TABLE XXII (con't)

16.	Freeboard	1.49 feet
17.	Metacentric height	+2.18 feet
18.	Focal height of Buoy	15.9 feet
19.	Isotope selection	Strontium-90
20.	Halflife	28 years
21.	Biological danger	Great
22.	Type radiation	Beta, Bremsstrahlung
23.	Fuel selection	Strontium Titanate
24.	Initial fuel loading	188,555.1 curies
25.	Fuel size	5686.6 grams
26.	Encapsulment material	0.25 inch Hastelloy C
27.	Absorption material	0.25 inch Hastelloy C
28.	Generator type	Thermoelectric, P-N type
29.	Generator efficiency	5%
30.	P-N type semiconductors	N, lead telluride, bismuth doped P, lead telluride, sodium doped 26 P-N pairs, 0.5 volt/pair
31.	Biological shield	13.3 cm of lead
32.	Outer shield dose rate	2.5 mr/hr
33.	Total thermoelectric generator weight	3956.3 pounds
34.	Electrical system	12 unit cell nickel-cadmium batt. 12.0 volt, D.C. output voltage regulator, trickle charge, maximum current 1.5 amps static D.C. converter for power flattening
35.	Mooring chain	1.25 inch steel link chain
36.	Scope	3 to 1

TABLE XXII (con't)

37.	Attachment bridle	400 pound 1.25 inch Y fitting
38.	Sinker weight	6500 pound concrete block
39.	Underwater buoy protection	Coal tar derivative dip 0.75 inch galvanized steel cable with 2-144 pound zincs
40.	Above water buoy protection	Corrosive resistant paint
41.	Total system weight	23,568 pounds
42.	Total cost, 5 year period	$100,252.46
43.	Excess cost over standard buoy	$72,412.56
44.	Minimum on-station tender check	650 days
45.	Year of economic feasibility	1976
46.	Isotope control	Atomic Energy Commission
47.	Buoy control and maintenance	U. S. Coast Guard
48.	Potential use	Existing 4000 powered buoys
49.	Expected buoy use by 1980	Up 100% (average)
50.	Feasibility of system	Can be produced now

RECOMMENDATIONS

Radioisotope power programs have greatly expanded since the initiation of the SNAP series for aerospace applications. The knowledge of isotope potentials and biological shielding requirements has been thoroughly explored with only the energy conversion devices presenting possibilities of improvement. Current thermoelectric devices with their five percent efficiency present a definite challenge for improvement, and technological advances should soon appreciably increase the effectiveness of both the thermionic and thermoelectric converters. Although work is proceeding with dynamic conversion systems for larger power needs, it appears Strontium-90, Cobalt-60, and Plutonium-238 will be the primary static low power isotope fuels. With an optimum buoy design carrying a maximized navigational payload, it is merely a question of overcoming existing monetary disadvantages, as the isotope buoy is superior in all other aspects.

Assuming normal technological advances in these fields of engineering, the one recommendation of this thesis is to promote the goals of two major governmental agencies into one joint solution. The Coast Guard, with some 4,000 powered buoys and numerous lighthouses faces a large growth and expansion of its aids to navigation system as noted by several included studies; and the Atomic Energy Commission, with increasing nuclear fission wastes and hence a growing stockpile of isotopes such as Strontium-90 could easily not only solve their

respective problems, but help create markets for future growth of isotope power. As described earlier, the price of isotopic fuels is an inverse availability function; the larger the demand, the lower the cost. By using current prices, it was noted that fuels prices have halved since 1964, and this isotope buoy would be economically feasible by 1976. If the Coast Guard and Atomic Energy Commission joined forces before this date, this volume of business would not only assure the Coast Guard of a reliable, efficient buoy network, but would open hopefully huge markets for the Atomic Energy Commission's isotope power systems.

Naturally larger buoys with longer on-station durations, or improved isotopic power systems might later be tried, but the immediate goal is to realize a design of this nature and simply <u>promote it</u>; multiple benefits will then be soon forth coming.

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